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Ageing and Restoration of Transformer Windings

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RESULT (summary)

The transformer winding is the strategically most important part of a transformer. Failures in the winding results in catastrophic events and long outages. Several of the failure modes relevant to a winding are due to or related to increased water content of the insulation. The paper insulation is aged through a thermally activated reaction, where water is an important accelerator. An equation describing this ageing is available for both Kraft paper and for thermally upgraded paper. The equation can be used for estimation of life consumption/extension for the paper insulation.

Paper ageing will produce several chemical by-products that may serve as diagnostic indicators of the ageing.

It is suggested to start tests on performing only reinhibiting on lightly aged oils to save the more costly reclamation.

For getting a life extension on a transformer winding one needs to extract the water from the winding. Methods for oil reconditioning and reclamation are not particularly efficient for drying of the cellulose, which is where the most of the water stays. Vapour phase and hot-oil-spray are more efficient drying methods. When drying a transformer care must be taken to retighten the windings to avoid later movement during short circuit stresses.

The role acids created in the oil and in the paper has on ageing of paper is not fully understood. Solubility for such acids in oil and in paper also needs further studies to be understood.

KEYWORDS

SELECTED BY AUTHOR(S)		
	Transformer windings	Paper ageing
	Maintenance	Water

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SUMMARY

From a risk based point of view one should focus on the winding being the strategically most important component in a transformer. The On-Load Tap Changer (OLTC) is the most maintenance intensive component, probably best cared for by a parameter based maintenance scheme.

Lately, concern about the present status and the future development of the technical condition of large power transformers has grown. This stems partly from the ever-increasing age of the transformer population – bringing up questions about restoration and reinvestments – and partly from a new regulatory regime[1] where the consequences from a havoc of a large transformer gets more severe. Additionally, there is a wish to upload the transformers both in a stationary operation and during transient emergencies.

International experience is not necessarily relevant for Norwegian conditions. Differences in design, manufacturing processes and environmental conditions may play a role. For example bushing failures are rarely experienced for HV-transformers in Norway, while coming high on the international lists of failure causes.

The on-load tap changer (OLTC) tops the list of failure causes. At the same time we know that this is the most maintenance intensive component in a transformer. In particular, this is a problem for transformers serving industrial loads like metal melting plants, electrolysis of aluminium etc. Transformers in the central grid do not all have OLTCs. We are of the opinion that the OLTC problems to a large extent can be met by revisions and renewal. In the future, diagnostic tools like acoustic fingerprinting [1] and dynamic contact resistance (used by KEMA) can be expected to be more readily available and be of help in setting up maintenance schemes for tap changers. Full renewal is an alternative to repair/revisions.

In international failure surveys the winding comes high on the list of failure causes. A failure resulting in full short circuit in the winding will often have dramatic consequences for the transformer and its environment. At the same time the outage times get long. It can take weeks to get a replacement transformer, months to get a rewinding and around one year to get a new unit delivered. The consequences in terms of penalties etc. can easily mount to hundred million NOK. From this point of view the winding becomes the most prominent part in a risk analysis. The observation that the failure probability due to ageing is low will surely not be valid for the future. Knowing that about 40 % of the units are 30 years or older and that about 20 % are older than 40 years, one can foresee an increasing risk for this type of failure in the future.

High water content in the transformer insulation increases the risk of failure modes involving discharges, impulse flashover and paper ageing. Thermal ageing accelerated by increased humidity in the paper seems to be the most severe problem for the Norwegian transformer population.

[1] Penalties have to be paid for energy not delivered when the outage exceeds 3 minutes. The tariffs are for unplanned outages: NOK 50 per kWh for industrial loads and NOK 4 per kWh for household.

Water ingress into the insulation system and consequential discharges, creeping tracks and reduced impulse withstand voltage [2] seems to be a problem also relevant for Norwegian conditions.

Several of the failures experienced during the later years may be explained by reduced impulse withstand voltage. Model experiments show that an ac pre-stressed insulation (3-4 kV/mm) gets a 25-30 % reduction in the switching impulse withstand level (SIWL), when wet fibres (2-3% water in cellulose) are present. Electrostatic forces pulling particles into highly stressed oil volumes explain this [3].

At increased loads (i.e. temperatures above the boiling point of water) there is a risk that water vapour bubbles are formed in the oil around wet cellulose. Discharges may occur in the bubbles and a flashover may result if this occurs in the windings.

The same may occur when the gas content in the oil gets so high that the sum of the partial pressures exceeds the static pressure in the oil. It is mainly the nitrogen content that plays a role here. Degassing of the oil is an appropriate way of avoiding this risk.

In model experiments, we have also seen that the discharge inception voltage is significantly reduced when the cellulose gets wet [4].

Two failure types brought up by Sokolov [2] relates to the same main problem: Mechanical weakness and cellulose ageing. The end scenario is the same: A short circuit resulting in mechanical stresses the winding cannot withstand. Ageing of the cellulose will reduce the mechanical strength of the winding. The mechanical strength of the paper drops with 80% when decaying from new with a degree of polymerisation (DP) of some 1000 to a DP of 200. When the paper arrives at a DP value of 200 the interfibre bonds also are weakened. A DP value of 200 is generally accepted as the end of life criterion of the paper. Again water in the insulation system increases the risk by increasing the ageing rate. An increase from about 0,5% to about 3% water content in cellulose increases the ageing rate approximately 15 times.

Oil ageing is mainly an oxidation process. It is suggested to reinhibit the oil if the inhibitor content goes below 20% of new value. In the Norwegian standards it is now recommended to reclaim the oil before the inhibitor is fully consumed.

Oil ageing introduces mainly two risks: Formation of acidic compounds that accelerate paper ageing and at a late stage, sludge formation and reduction of the cooling efficiency of the winding. Earlier one focused mainly on acidity when considering exchanging or reclaiming the oil in a transformer. Presently, one focuses more on inhibitor consumption and reduction in interfacial tension as precursors to oil ageing. Attention is now growing on the advantage of reclaiming the oil at an early stage when the processing time is short and acidic compounds still have not been formed and absorbed in the cellulose. Normally one reclaims the oil prior to adding new inhibitor. If the reclamation is omitted, the lifetime of the oil (i.e. time to increase in acidity) will be shorter (around 30 – 50%), but the costs will also be much lower. It is suggested to start field tests with

reinhibiting the oil without reclaiming it, and thereafter monitoring the development of parameters like interfacial tension, tan δ etc.

Paper ageing increases with increasing temperature (doubles for every 7°C) and with increasing water content. Thermally upgraded paper has a reduced ageing rate and is less sensitive to moisture (ageing rate doubles every 10°C).

Paper ageing increases with temperature (T). This dependence is described by the so-called activation energy (E) in an equation expressing the potential lifetime of the paper based on ageing kinetics, as described by Emsley [9]:

$$Lifetime = \frac{\frac{1}{DP_{Start}} - \frac{1}{DP_{End}}}{A_{Condition}} e^{\frac{E}{R(T+273)}} \qquad [h]$$

For Kraft paper E is estimated to be 111 000 ± 6 000 $Jmole^{-1}$. For thermally upgraded paper we have found E to be 81 000 $Jmole^{-1}$. R is the molar gas constant (R= 8,314 $Jmole^{-1}K^{-1}$).
In a new transformer the DP value is about 1000, and there is a general opinion that a DP value of 150-200 indicates end-of-life for the paper. Contaminants like e.g. water, oxygen and acids accelerate the ageing. This dependence is described by the so-called pre-exponential factor ($A_{Condition}$). Pre-exponential values are calculated (see Section 3.3). For Kraft paper they are in line with what has been found in the literature [9]. The values found for thermally upgraded paper shows that ageing goes slower by a factor of about three in the temperature range from 70°C to 130°C , and that the ageing is not as sensitive to moisture as for conventional Kraft paper.

2 FAL is an ageing by-product and can serve as an indicator of ageing of Kraft paper. For thermally upgraded paper no increase in 2FAL content can be seen. CO and CO_2 are also indicators of paper ageing

It is impossible to get an accurate condition assessment without opening the transformer tank and taking paper samples. One is left with the possibility to assess the condition via model studies and/or diagnostic measurements. Model studies are based on the ageing kinetics discussed above using relevant operating temperatures and service conditions like e.g. measured water content.
The diagnostic measurements will mainly be based on oil analyses. In our experiments the content of 2FAL, acids and water is seen to increase with increasing paper ageing. In the literature, correlation between formation of CO and CO_2 and paper ageing has also been shown. None of these parameters give direct correlation to paper condition, and they will probably only be meaningful within a trend study or compared with data from a larger transformer population. Also one must be aware that oil regeneration and reclamation will remove some or all of the indicators.

Oil reclamation is useful for avoiding sludge and organic acids that may later accelerate the paper ageing. To reduce ageing of the paper one must either avoid the ingress of water into the transformer using e.g. moisture absorbers or barriers, or remove it by an efficient process like e.g. the vapour phase or the hot oil spray methods.

Oil reclamation has mainly been focused on the oil condition. As focus now moves to the ageing of the winding and the impact of water on this ageing (and also on other failure modes) one has to reassess the maintenance philosophy. Oil reconditioning and reclamation is not very efficient for removing water from the paper and pressboard, where most of the water is found. Even if the temperature is kept high (e.g. during service) to increase the drying efficiency only a fraction of the water is removed by these processes. A drying effect on the cellulose has been claimed but is not well documented. To really remove the water one has to apply more efficient methods like e.g. vapour phase drying or hot oil spray. Vapour phase drying is to our knowledge only applicable in transformer factories. The hot oil spray method can be used on-site. The oil is removed from the transformer. Then the water is evaporated from the cellulose by spraying it with hot oil and then removed by vacuum equipment. Often the winding is heated by circulating low-frequency current through it.

Presently, maintenance techniques developed for hydraulic systems are promoted for use on transformers. Often one will find that such techniques either are not efficient or less suited for an oil/paper insulation system, where the oil volumes are comparatively large. It is advised to carefully assess such systems before taking them into use.

It is probably more cost efficient to hinder the water from getting into the transformer. Careful dimensioning and maintenance of silica gel filters in breathers is necessary. Introduction of rubber membranes in the expansion tank is another useful technique.

One needs different maintenance strategies for older moist and contaminated units and for newer units in a good condition

During many years the transformers have often been neglected. For many units the conditions are quite severe – moisture content in the cellulose in the 3% - 4% range is not rare. The oil has often been allowed to deteriorate severely. As the amounts of water can be large (tens to 100 kg) and it is difficult to remove it, different strategies should be applied depending on the transformers condition.

For well-kept transformers one should avoid increase in water content by using moisture absorbers/barriers in the breathers. Moisture absorbers in oil can be useful. They do not need to have a high capacity to cope with small amounts of water. Oil quality should be monitored and actions should be taken to reinhibit/reclaim the oil, and one should not allow it to get a high content of acids. Reclaiming oil that is only lightly oxidized are less expensive than reclaiming a heavily aged oil.

Full reclaiming can reduce sludge formation in heavily aged oils and to some extent get the ageing byproducts out of the paper. The usefulness of oil reclamation for the condition of paper (acidity etc) is not well documented. One has to wait for return of experience from the field and possibly also make laboratory experiments to understand more of this.

Full oil reclaiming on a wet transformer (e.g.> 2-3 % in the paper) cannot be recommended, as the water content will remain almost unchanged and dominate the ageing. To get a life extension one has to get the water out of the paper. Full drying of a transformer winding should not be done without considering the need of retightening the winding. The paper insulation swells when it gets moist and shrinks again when it is dried. During this a plastic deformation will take place. Furthermore the paper loses weight when ageing. Both these effects will contribute to a reduction of clamping forces after drying of the winding.

Water content in cellulose is today measured indirectly via oil samples and moisture balance curves. New methods for dielectric response measurement have a potential for giving more accurate condition assessment and also for quality control of winding drying.

Today water content is measured by taking an oil sample from the bottom of the transformer tank. If the temperature is known one can via curves for moisture balance calculate the moisture of the cellulose. In the Norwegian "Oil Handbook" schemes for such estimations are given. The method depends on the temperatures being stable over time to get good results.

Lately a new method – the so-called "Dielectric Spectroscopy" has come into focus. One measures polarization and/or depolarization currents in the transformer between the HV- and LV-windings. The transformer has to be off-line during measurements. When knowing the conductivity of the oil (can easily be measured) and some data about the relative amounts of solid and liquid in the main gap, one can calculate the conductivity and the polarization of the cellulose. From this the average water content can be estimated. Presently one knows the impact of water on the dielectric response of paper. The influence of ageing byproducts is not well known.

The dielectric response method offers a more direct method for measuring the water content in the cellulose than today's oil sampling. It has the potential of becoming a useful tool both for condition assessment and for quality assurance of performed reconditioning/drying actions.

In a risk assessment one must in addition to the technical condition of the transformer consider the short circuit currents and over-voltage conditions at the point in the grid, the redundancies in the grid and the importance of the transformer in respect to grid location and the load and customer groups.

One must distinguish between the end-of-life criterion for the paper and the end-of-life criterion for the transformer. We support the idea that a DP-value of 200 is an appropriate end value for the paper. However, the reproducibility and accuracy in the DP measurements are not very high and the paper quality will vary within the winding insulation and within the transformer. Therefore, even if paper with a DP-value of 200 is found within the transformer this does not necessarily depict the general condition of the transformer. Presumably, the average DP value is a better condition indicator than the lowest observed DP-value.
Furthermore, looking blindly at the paper quality is too simple. When assessing the end-of-life of a transformer one should also consider the frequency and magnitude of the short circuit stresses that may occur. Also the importance in the grid, redundancies, type of load etc have to be assessed, together with the emergency preparedness of the maintenance organisation.

1 BACKGROUND

Description of the Norwegian transformer population, and risks it is exposed to.

From a design and materials point of view the Norwegian transformer population is fairly homogeneous. From a strategic point of view the transformer winding is the most critical part of the transformer. Several of the failure modes the winding is exposed to, relate to high water content in the insulation. Many of the transformer units have a high age, and a significant part of the population has high water content.

1.1 Transformer population in Norway

In Norway the value of the high voltage transformer park (i.e. 120 kV and above) is some 10 billion NOK [5]. The age profile for this population is shown in Figure 1. The failure rates are quite low, but as the ageing process is an irreversible process, considerable attention is focused on issues like life extension (postponing of reinvestments), refurbishment and diagnostics. In 10 years 25 % of the population will be more than 50 years and in 20 years more than 40 % will have an age above 50 years.

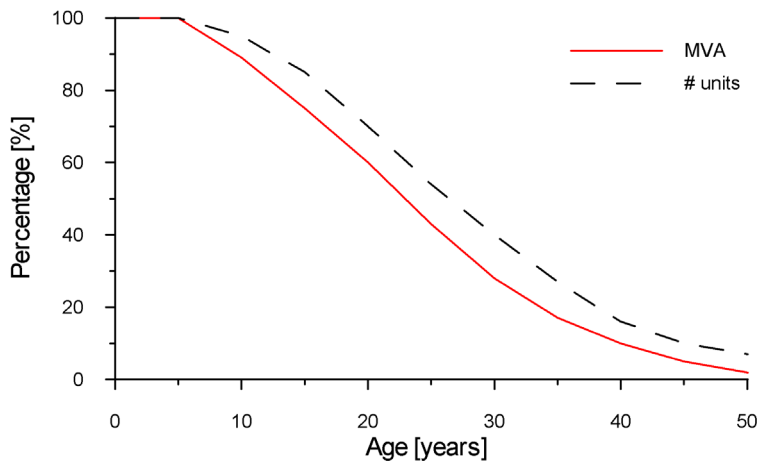


Figure 1: Estimated age profile of the high voltage transformer park in Norway.

1.2 Transformer failure surveys

In Norway the transformer availability has been good. Recently a couple of forced outages of larger 300 kV units have occurred and the failure rate seems to have increased. Internationally, the statistics has been investigated by CEA [6] and Cigré [7] with results as shown in Table 1 and Table 2. Both surveys conclude that the failure rates increase with age and voltage class. The Cigré survey estimates the average failure probability to lie around 2% per year (in 1983). From a strategic point of view the winding is the most vulnerable part of the transformer; a tap changer may easily be taken out for renewal or overhaul, while the winding is barely accessible. Furthermore, winding failures will result in long outage times.

Table 1: Canadian outage statistics [6].

Voltage Classification [kV]	Time Period			
	1985 - 1989		1990 - 1994	
	Outage Rate [%]	MTBO [year]	Outage Rate [%]	MTBO [year]
110-149	0,0085	118	0,0479	21
150-199	0,0491	20	0,1732	6
200-299	0,0112	89	0,0451	22
300-399	0,0219	46	0,0776	13

Table 2: Probability ranking of failure cause (planned and forced outage) [7].

Probability Ranking	With On-Load Tap Changer (OLTC)	Without On-Load Tap Changer
1	Tap-changer	Bushings
2	Winding	Winding
3	Tank and Oil	Tank and Oil
4	Bushings	Other accessories
5	Other accessories	Core
6	Core	Tap-changer

From Doble and ZTZ-service (An Ukrainian based institution) return of experience shows that [2]:

- 70 % of the failures occur on units older than 30 years.
- 50 % of the failures originate from OLTC's and bushings.
- 15-20 % are due to reduction in impulse withstand voltage due to water and particles in the insulation.
- 3-5 % are due to excessive ageing (e.g. poor cooling).
- 10-15 % are due to mechanical weakness/winding distortion.
- Some gassing problems in older designs are due to induced losses.

Failures in OLTC may be avoided by a parameter based (time in service, number of operations) maintenance scheme. The unit is also fairly simple to exchange/renew, with short delivery time. Failures in the winding will necessarily result in long outage times. The paper insulation in the winding is also subjected to steady ageing, so sooner or later it will wear down. In case of a winding failure a long repair time or a full renewal cannot be avoided.

1.3 Transformer design in Norway

The transformer population for the HV regional and central grids in Norway is quite homogeneous; only a few factories dominate (National Industri, ASEA Per Kure, Pfeiffer, and ABB) up to the mid 1990's. The designs of the ASEA and the National Industri transformers are quite similar; thickness of the winding insulation (paper wrapping) is about the same as are the

insulation distances. Typically the thickness of the turn-to-turn insulation is in the 0,6-1 mm range, except for regulating windings, where it can be up to some 4 mm.
Ribs and spacers are typically produced of 1-5 mm pressboard. The barriers will normally be of 1-2 mm thickness. The quality of wooden elements (e.g. plywood and permawood) has not been investigated.

The thermal aspects in the designs are covered by international standards. This should give about the same thermal stresses on the paper in the various designs. From an ageing point of view the differences are probably insignificant. However, during the past some technological shifts influencing the ageing have occurred:

In former times the transformers were dried in ovens, while now the vapour phase technique dominates. In principle both methods may give equally low moisture. In practice the oven method is more time consuming and in periods where the annual production volumes were high the drying periods may possibly have been reduced. Somewhat higher initial moisture contents have to be expected from these generations. The vapour phase technique was introduced at National Industri in mid 1960th and at ASEA in 1966. The awareness of the moisture problem has increased with time. Modern transformers will in general always be dried to or below the 0,5% level.

In general transformers in Norway have been delivered with inhibited[2] naphtenic oils. Here Nynäs 10X, Shell Diala DX, Esso Univolt are some of the better-known oils. There are possible differences in the insulating liquids in respect to composition and additives like e.g. inhibitors, metal deactivators etc..

For early designs the winding was impregnated with shellac. In such old units the paper layers still stick together.

Practice has probably also varied in respect to covering metal surfaces on the earth side; (metals may have a catalytic effect on oil decomposition).

Most transformers are delivered with a winding insulation made of Kraft paper. From mid 1960's to the end of the 1970's National Industri offered transformers with thermally upgraded paper (e.g. Insuldur®). The paper was partly imported and partly produced at Borregaard under a Westinghouse licence.

Winding clamping is usually done without elasticity by adjusting bolts and wedges. In rare cases springs were used.

The design rules for short circuit withstand capability have changed with time. After 1990 design rules specified that forces due to short circuit stresses had to be compensated from the clamping of the winding itself, without taking into account support from neighbouring windings and the core.

[2] Inhibited means that a chemical is added which postpones the oxidation of the oil itself by removing free radicals .

Apart from differences originating from the design and manufacturing process, service conditions and maintenance schemes will have an impact on the condition. Loading of transformers may vary. Usually transformers in the Norwegian grid are – as an annual average - loaded well below their rated load, and they have the highest load in winter, when cold. Industrial transformers and generator step-up (GSU) transformers will be higher loaded. Information about historical load profiles is useful for preliminary analysis of the technical condition.

Many utilities have not cared enough for their transformers. Water content and neutralisation value have been allowed to increase over time and Silica gel filters with colours indicating full moisture absorption has been seen. In these cases one can expect severely bad conditions of the insulation system. A significant percentage of the population has moisture in the 3-4% range.

Oil analyses have to a various degree been performed and will in the future be collected in a large national database.

2 AGEING OF THE INSULATION SYSTEM

Description of transformer insulation materials and their ageing mechanisms.

Cellulose is a material consisting of long chains of glucose rings. The average number of rings in the cellulose molecule is denoted the degree of polymerisation (DP-value). During ageing these chains break up (i.e. the DP-value is reduced) and the mechanical strength of the cellulose and paper is weakened. An Arrhenius relationship can describe this ageing. Water and high temperatures accelerate the ageing of paper. Oil ages mainly by oxidation. Metals (e.g. copper) will have a catalytic effect on the ageing of the oil. During ageing of both paper and oil a number of chemical by-products are created. These may serve as diagnostic indicators.

2.1 A little paper chemistry

Paper consists mainly of long cellulose molecules, some per cent hemi-cellulose and about one per cent lignin. (In wood the lignin binds the cellulose fibres together, while lignin and hemicellulose are absent in cotton.) During manufacturing of paper from wood pulp one tries to wash away as much hemi-cellulose and lignin as possible leaving only the cellulose fibres. Kraft paper is the most common type of paper used in transformers. It is made from wood paper pulp cooked at high temperature and pressure. NaOH and Na_2S are used for dissolving the lignin and free the cellulose fibres. The chemicals are thereafter washed away and fibres are formed to a web, which is heated and dried on large rolls or between plates.

The cellulose molecule is formed by a series of glucose rings, linked together with an oxygen bridge. For cellulose this is called a β-glycosidic bound. The average length of the cellulose molecule is described by the number of rings and called the degree of polymerisation (DP-value). It is the free hydroxyl groups (-OH and $-CH_2OH$) that contribute to the hydrophilic and polar nature of paper. These groups also are the basis for intermolecular bonding between the cellulose molecules and cause the high crystallinity of the microfibrils. The cellulose fibres consist of many oriented layers of microfibrils, which are bonded together by lignin.

By varying the pressing and drying techniques, the density and surface smoothness of the paper or pressboard may be varied. The paper or pressboard can also be chemically treated to thermally stabilize it. One can either use cyanoacetylizing to modify the OH-groups of the cellulose molecule or use additives such as urea, melamine etc to reduce the oxidation rate of the paper.

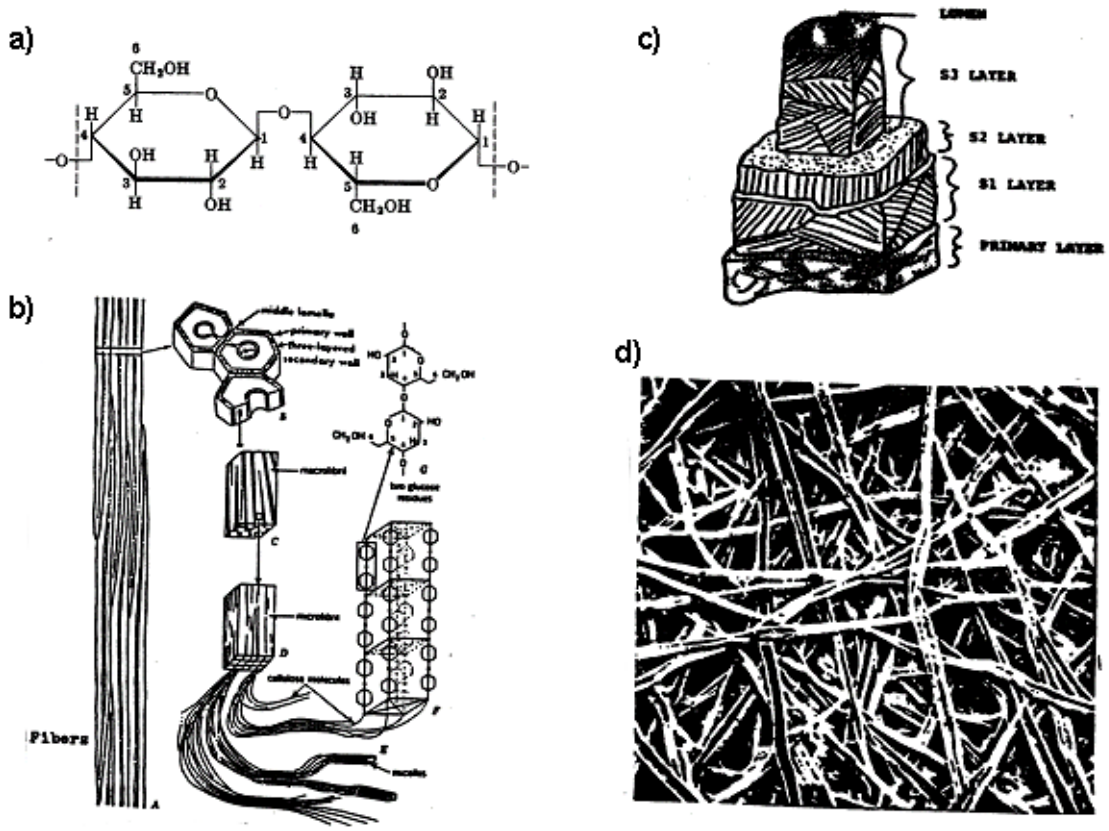


Figure 2: Cellulose: a) The cellulose molecule, b) Cellulose molecules forming microfibrils with crystalline regions and microfibrils forming one fibril, c) Model of a wood fibre with layers of fibrils, d): Web of fibres in paper [8].

2.2 Ageing of paper

The cellulose in windings is either in the form of paper used as insulation covering of the conductors or in the form of pressboard as spacers, ribs and barriers. Various qualities of paper and pressboard exist. For the Norwegian utilities the most interesting is the normal Kraft paper and one type of thermally upgraded paper (Insuldur).

Over time the mechanical strength of the paper will degrade. The tensile strength and bursting strength are reduced, which results in a reduced mechanical withstand ability of the winding. At the same time the grammage (weight per square meter) of the paper is reduced. The reduced density of the paper may result in a reduced clamping force. The dielectric insulation capabilities are practically not affected.

The ageing of paper is normally split in three mechanisms:
Pyrolysis: Heat alone results in breaking of the β-glucosidic bonds and opening of the glucosidic rings. This process results in formation of free glucose molecules, water, CO and organic acids. Above 200°C other reactions will take place.
Oxidation: Normally oxidation results in a weakening of the β-glucosidic bonds and formation of water. This is mainly due to the three hydroxyl groups in each ring (-OH). The process will be accelerated by acidic or basic conditions.

Hydrolysis: This is the strongest ageing factor for paper. It results in breaking of the cellulose molecule and adding of water at the point of chain breakage. Free glucoside rings are formed. As water is formed during pyrolysis and oxidation, this will later add to hydrolysis of the cellulose.

Ageing of paper will result in formation of water, acids, CO, CO_2 and various by-products from the further breaking of the saccaride rings. Among these the furans and in particular 2-Furfur-aldehyde (2FAL) has drawn the main attention lately. As it often is difficult to get paper samples from a transformer, one is left with possibilities of estimating a transformer's condition from the above-mentioned descriptors, along with existing knowledge about its load history.

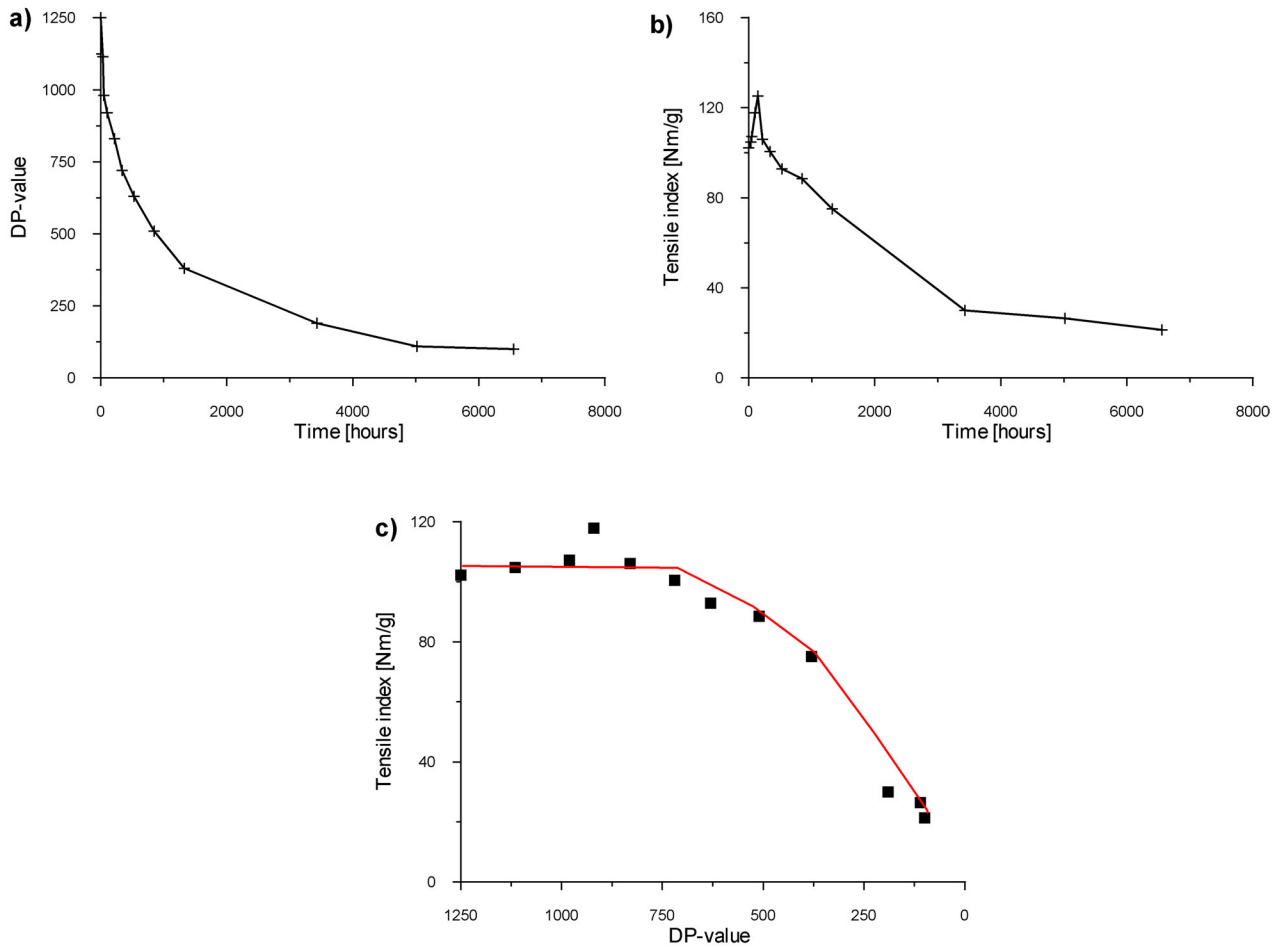


Figure 3: Reduction of DP-value (a) and tensile index (b) for Kraft paper with time (3% water at 110°C). The correlation between tensile index and DP-value (c).

As the cellulose fibres break up into smaller molecules the mechanical strength of the paper is reduced. This relation between the chemical ageing and the mechanical strength is shown in Figure 3 (tensile index: See Page 24). What is interesting from the practical point of view is the mechanical strength of the paper. However, the ageing is possibly more understandable if seen through a chemist's eyes. As shown in Figure 4a, the degree of polymerisation (DP-value) is reduced more quickly with time as temperature increases. If instead plotting this as 1/DP versus time (Figure 4b) the curves change to fairly straight lines where the angle of rise describes the reaction rate. When taking the natural logarithm of the reaction rate and plotting this versus the inverse absolute temperature (a so-called Arrhenius plot) the resulting curve is a straight line; this

is what is described as a thermally activated process. The development here may be described as a first order process. This means that the reaction rate is constant over the ageing period, and that logarithm of the reaction rate decreases linearly with the inverse of the absolute temperature. The ageing may be described by Equation (1):

$$\frac{1}{DP_{aged}} - \frac{1}{DP_{new}} = Ae^{\frac{-E}{R \cdot T}} \cdot t \qquad (1)$$

Here, E is denoted activation energy. The higher E is the more the reaction rate k = Aexp(-E/RT) increases with temperature. As sketched in Figure 4c the reaction rate may vary with the moisture content. It gets lower if the water content is reduced and higher if the content is raised.

The correlation between the average number of chain scissions (η) and the DP values of the cellulose molecule measured before and after an ageing period is given by the equation:

$$\eta = \frac{DP_{Before}}{DP_{After}} - 1 \qquad (2)$$

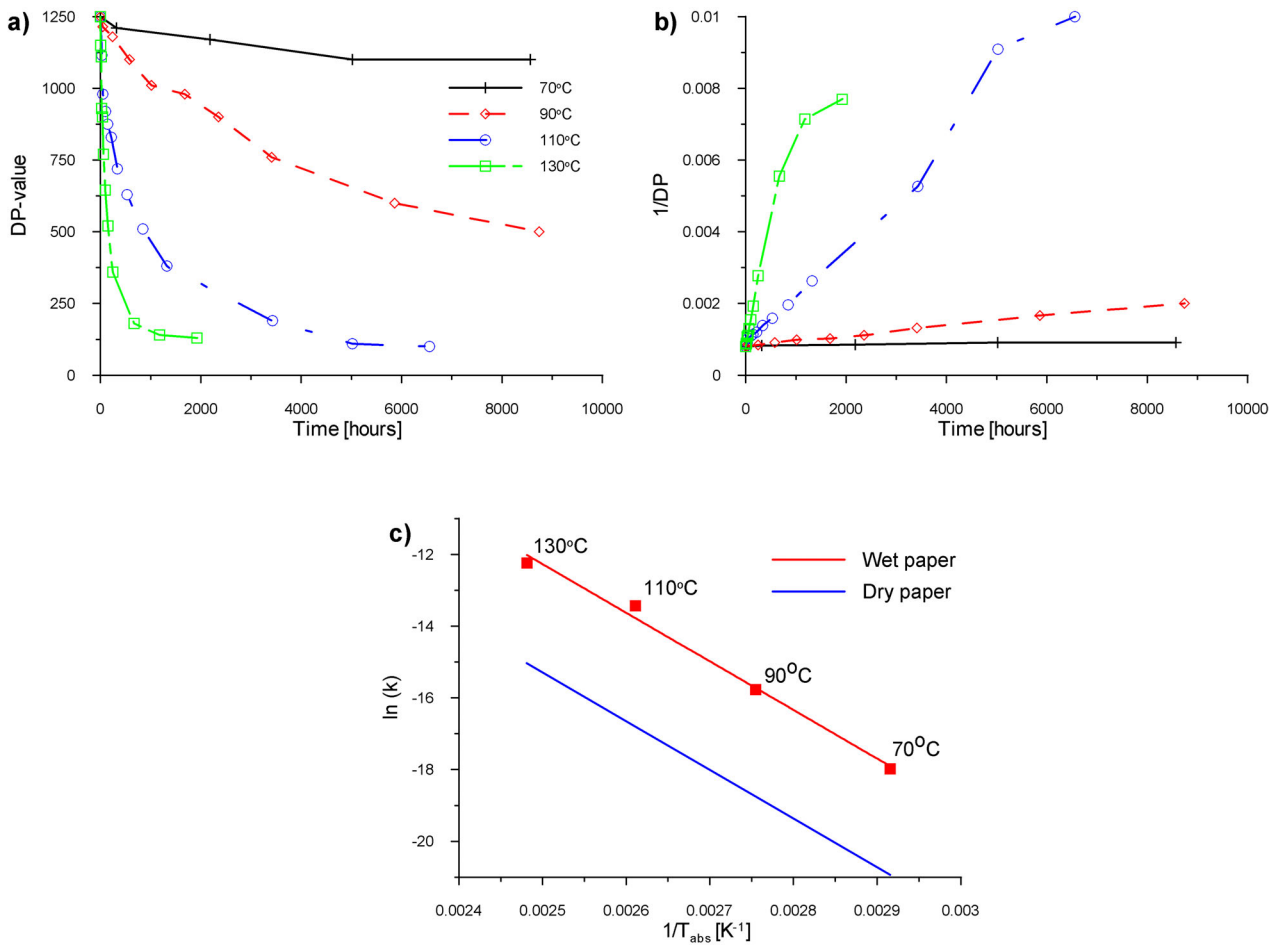


Figure 4: Ageing of Kraft paper with 4 % humidity versus time for four different temperatures. a: DP-value versus time, b: 1/DP versus time, c: Reaction rate versus inverse absolute temperature. (Wet paper is real data, dry paper is somewhat idealised; i.e. given an activation energy equal to that of wet paper.)

From Equation (1) one can see that the higher the activation energy E is the more the reaction rate increases with increasing temperature. In Figure 4c the Y-axis is the natural logarithm of the reaction rate; ln k. For example: By increasing the temperature from 70°C to 90°C the reaction rate then increases with $e^2 = 7{,}4$. I.e. by increasing the temperature 20°C, the aging goes 7,4 times faster. The term A in Equation (1) shows how "high" in the plot the curve lies. We see from our idealized figure that increasing the water content lifts the curve by about 3. I.e. adding water to 4 % in the cellulose will increase the ageing by $e^3 = 20$. By at the same time increasing the water content and increasing the temperature by 20°C the ageing rate increases by a factor $e^5 = 148 = 7{,}4 * 20$. Further information about this can be found in a paper by Emsley et al [9].

Kraft paper will normally have a DP-value of 1200 when new. After having gone through the drying process in the transformer factory the DP-value is reduced to roughly 1000. Paper with a DP-value of 200 is often considered as having reached the terminal stage. As seen from Figure 3 the remaining tensile strength is about 20 % of that of new paper. One further argument is that the inter-fibre forces now are reduced. As shown in Figure 5 the tensile strength of paper is higher for a short test specimen, with the jaws initially fixed with zero spacing, compared with a test where the jaws of the test bench are placed with a distance in-between. Looking at the ratio between the two shows that it is constant down to a DP of about 200; whereafter the long-span is more quickly reduced. This indicates that the inter-fibre forces are reduced.

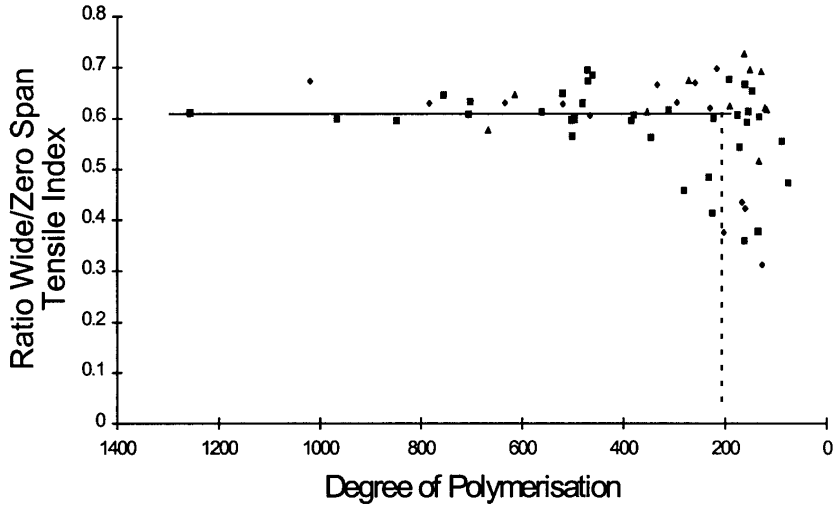


Figure 5: Tensile strength of Kraft paper: Ratio between long-span and zero-span [10].

In a real transformer the temperatures and the condition will vary throughout the winding and also through the paper layers around a conductor.

In addition to the reduction of the mechanical strength of the paper the density of the paper is reduced; there is a weight loss. This weight reduction results in a shrinking of the paper and thereby reduced clamping forces. Swelling resulting from water absorption may more than compensate this shrinkage.

2.3 A little oil chemistry

Mineral oils are produced from crude oils by a distillation and a refining process. This all influences the properties of the final product. The properties are a compromise between wishes for good electrical properties, high oxidation stability, high gas absorption capability, low viscosity and pour point, and a high flash point. Specifications are found in the standards [11, 12]. In Norway the oils are almost always inhibited (i.e. an oxidation stabilizer is added). Normally the inhibiting is done by adding 0,3% Ditertiary-Butyl Paracresol (DBPC).

The molecules in a mineral oil vary wildly in size and structure. The oil molecule shown in Figure 6 is a hydrocarbon and consists of one aromatic ring, two naphtenic rings (without double bonds) and linear (paraffinic) chains. Oils are often characterised by the average percentages of aromatic, naphtenic and paraffinic bonds.

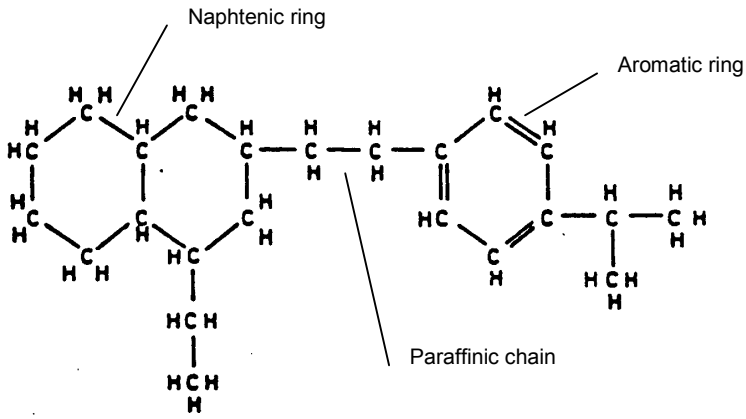


Figure 6: Example of an oil molecule

Often the various oil companies buy from each other. During the late seventies Esso lost access to Venezuelan crude, which was the basis for naphtenic oils. They then advocated paraffinic oils (with pour point depressants[3] added). In Norway paraffinic oils were only delivered for the industrial transformers for a period. Possibly the composition of the naphtenic oils may have changed with time.

2.4 Ageing of oil

The main ageing mechanism of transformer oil is oxidation, this process is accelerated at increased temperatures (i.e. reaction rate is doubled every 6-8°C), and by catalytic effects of metals like e.g. copper. One can expect the oils to age differently due to differences in the basic crude oil and to differences in the refining processes. These differences may influence the oxidation stability of the oil. When hydrocarbon oils react with oxygen a number of organic compounds may be formed: Peroxides, aldehydes, ketones, alcohols, acids, etc. and in an advanced stage of oxidation also sludge. This ageing can be diagnosed by detecting increased acidity, loss factor and conductivity, a reduced interfacial tension, consumption of inhibitors, change of colour and in the end also the formation of sludge.

[3] Pour Point Depressant: Chemical agents that is used to give paraffinic oils a lower “freezing” point.

Depending on the refining process the oil may contain natural oxidation inhibitors, or inhibitors may be added after the refining process, together with e.g. metal deactivators etc. The inhibitors delay the oxidation, while at the same time being consumed. The time until the inhibitor content has fallen to zero is called the *induction period*.

3 EXPERIMENTAL RESULTS FROM PAPER AGEING

Description of ageing experiments on Kraft paper and thermally upgraded paper.

Ageing experiments were performed under various temperatures and conditions. The main results support the previously presented ageing model and parameters, possibly with somewhat lower temperature dependence. Both the ageing rate and temperature dependence of thermally upgraded paper are lower than for Kraft paper. From the results one can estimate paper ageing when knowing the temperature and moisture. During ageing Kraft paper produces 2-furfuraldehyde, which may be used for condition assessment. The same is not seen for thermally upgraded paper. It is also seen how both Kraft paper and thermally upgraded paper produce acids while ageing. Surprisingly, acidic oil did not cause much acceleration of the ageing when the paper was dry. Probably there is an unknown interaction between water and acids in the ageing process.

3.1 Description of ageing experiments

The ageing experiments were performed on pre-cut paper samples (121 mm long and 12 mm wide strips). 100 g of these paper strips were placed in sealed bottles (2320 cm^3) together with 1800 g of transformer oil. This added up to 1300 and 820 paper strips of Kraft paper and Insuldur respectively. (Insuldur is a thermally upgraded paper from Avery Dennison.) The bottles were placed in hot cabinets to age, and paper and oil were sampled throughout the ageing period. The oil to paper ratio was 18:1. The extra volume in the bottles allowed thermal expansion of the oil. The caps were equipped with a lead seal to avoid water diffusion.

Two types of paper were tested:

- Normal Kraft paper from Munksjø; with a thickness of 1,02 mm per 19 layers and a weight of 0,0758 gram per paper strip.
- Thermally upgraded creped paper from Avery Dennison; with a thickness of 1,01 mm per 14 layers and a weight of 0,1224 gram per paper strip.

The paper was dried under vacuum at room temperature for two days, and thereafter at 100°C and vacuum for two more days. When finally preparing the samples, a known amount of water was allowed to be absorbed into the paper and the samples were impregnated with dried and degassed oil. In all experiments with clean and degassed oil a naphtenic inhibited oil (NYTRO 10X) was used. The acidic oil was taken from a service-aged transformer.

Ageing experiments were carried out under six different test conditions for both paper types to investigate how the ageing rates depend on transformer conditions:

- Dry paper with filtered and degassed oil (A)
- Dry paper with filtered and degassed oil with 150 g molecular sieve (3A) in the bottle to absorb water (B).
- Dry paper with used oil from a transformer with an acidity of 0,16 mg KOH/g (C).
- Dry paper with filtered and degassed oil. The bottles were pressurized with dry air at a pressure of 2 bar for half an hour about every 14 days to get a high oxygen content (D).
- Paper with 1% water added (by weight) and filtered and degassed oil (E).
- Paper with 3% water added (by weight) and filtered and degassed oil (F).

For the series with water added this was done for Kraft paper and for Insuldur at the same time, assuming the water solubility to be equal in the two batches. Later measurements of water content in oil and paper gave some deviation between water measured in the paper and water calculated from moisture balance curves (Figure 26) for the two paper types. It is not given that the moisture balance curves for Kraft paper do apply for Insuldur. We assume that series A, C and D have the same initial moisture in the paper. We find it difficult to explain the fact that we measure a higher content of water than we added for series E and F. A high initial content of water can explain some of this. One would expect a slight deviation from what was added due to moisture remaining in the paper after drying. General measuring inaccuracies can be another explanation. Table 3 and Table 4 give an overview of the measured and calculated conditions.

Table 3: Initial amount of water in oil and paper for experiments on Kraft paper

Experimental condition	Water added to paper [% weight]	Measured in oil [ppm]					In paper [%]	
		20°C	70°C	90°C	110°C	130°C	Estimated from oil	Measured at 20°C
Dried paper	0	3,0	0,6	1,2	0,7	6,7	0,2	0,05
Molecular sieve	0	2,0	0,1	0,1	0	1,5	-	0,05
Acidic oil	0	1,7	0,8	1,0	2,5	19	0,2	0,4
Oxygenated oil	0	0,8	1,7	2,6	6	10	0,2	0,03
Medium water cont.	1,0	2,1	15	40	75	135	1,5	1,5
High water cont.	3,1	9,7	70	160	280	400	4,0	4,1

Table 4: Initial amount of water in oil and paper for experiments on thermally upgraded paper

Experimental condition	Water added [% weight]	Measured in oil [ppm]					In paper [%]	
		20°C	70°C	90°C	110°C	130°C	Estimated from oil	Measured at 20°C
Dried paper	0	0	0	1,1	2,5	7,5	0,2	0
Molecular sieve	0	1,6	0	0	1,5	3	-	0
Acidic oil	0	6,2	0	3,3	6	16	0,2	0,1
Oxygenated oil	0	1,9	3,5	2,2	5	10	0,2	0,1
Medium water cont.	1.0	3,7	1,6	3	52	85	1,0	0,7
High water cont.	3,1	17,3	75	160	260	370	3,5	3

The ageing was carried out at four different temperatures:

- 70°C
- 90°C
- 110°C
- 130°C

Throughout the ageing tests samples were taken of the oil and the paper. Attempts were made to sample the paper at equal intervals in the ageing process (i.e. each time the DP value was expected to have fallen with 100). Thus the samples were taken at shorter time intervals in the start than in the end of each ageing experiment. Each time an oil sample was taken, an equal amount of dried and degassed oil (60 ml) was injected into the test bottle, and the top of the bottle

was flushed with argon to avoid oxygen, prior to sealing the bottle again. The last was of course not done for the bottles where oxygen was added.

The following measurements were done on the oil:

- *Moisture content of oil* was measured on a 2,5 ml sample with a Karl Fischer Titration using a Metrohm 737 KF Coulometer with a 703 TI stand.
- *Acidity in oil* was measured on a sample of 20 grams according to IEC 60296, using titration with KOH and alkaliblue indicator
- The content of Furfural (2FAL) was measured on a sample of 10 ml sent to Electroinstitute Milan Vidmar in Slovenia.

The following measurements were done on the paper samples:

- *Moisture content of the paper* was measured on one paper strip taken from the hot test bottles. The samples were as quickly as possible transferred to the moisture extraction oven (Metrohm 768 KF oven) and moisture was thereafter measured with the Karl Fischer equipment. At 3 % moisture in paper the samples showed a moisture loss of 9% and 20 % when taken from test bottles at 70°C and 130°C respectively [13]. This was probably due to evaporation when transferring the sample from the test bottle into the oven.
- *The acidity of the paper* was measured on a 10 ml sample taken from an aqueous solution: Four paper strips were kept in 20 ml of distilled water for 3 days at room temperature to extract the acidic compounds from the paper. The titration was done as for the oil samples.
- *The tensile strength of the paper* was measured using a mechanical test machine with a jaw separation of 100 mm. The machine measures the force to stretch a paper strip to breakage and the percentage elongation. From this the machine reports the tensile index, percentage elongation at break, tensile energy absorption index and the modulus of elasticity index (similar to Youngs modulus/density) calculated for a standardised paper sample of 15 mm width with a grammage of 1 g/m^2. From this we recalculate the correct values for the actual sample size and density. Each test was done on ten sample strips. These tests were performed by PFI (Norwegian Pulp and Paper Research Institute) in Trondheim.
- *The degree of polymerisation (DP-Value) of the paper* was tested on six paper strips according to IEC 450. First the paper strips are dissolved into a “pulp” using a solvent and small milling glass beads. Then the viscosity of this pulp is measured. From the viscosity it is possible to calculate the average chain length of the cellulose fibres. These measurements were performed by Elektroinstitut Milan Vidmar in Slovenia by the kind help of Dr. Maja Koncan Gradnik.

More details about the experimental arrangement and expected accuracies can be found in a Project Memo [14].

3.2 Correlation between mechanical characteristics and degree of polymerisation

Perhaps the most basic results are the temporal development of the tensile strength and the DP-value of the paper samples. Figure 7 and Figure 8 show how these values vary with ageing time at different temperatures. For the mechanical strength shown here the tensile index is used. This parameter (the tensile strength divided by density of the paper) is better suited than the tensile strength for comparing the fibre strength between papers of different thicknesses and densities.

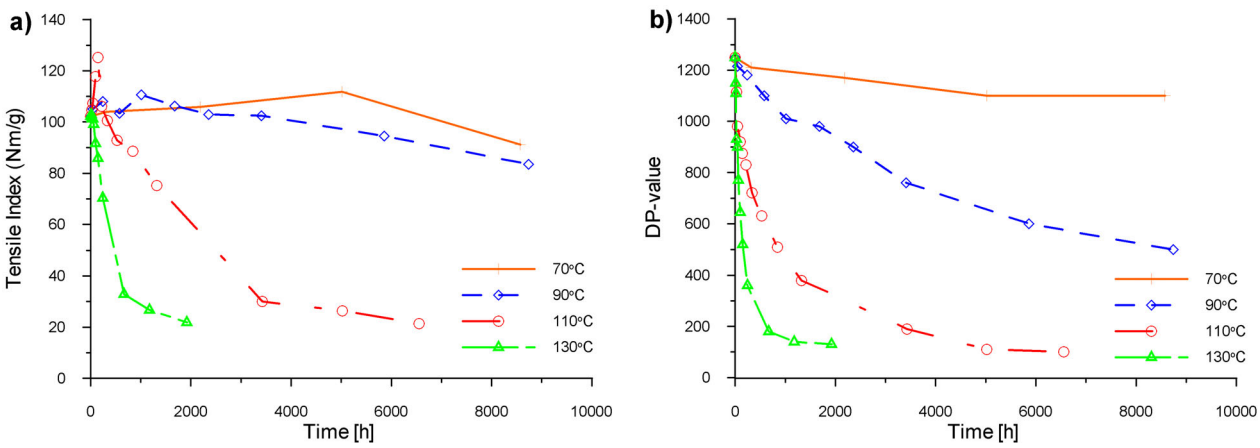


Figure 7: Tensile index (a) and DP-value (b) for Kraft paper with 3% moisture added versus time.

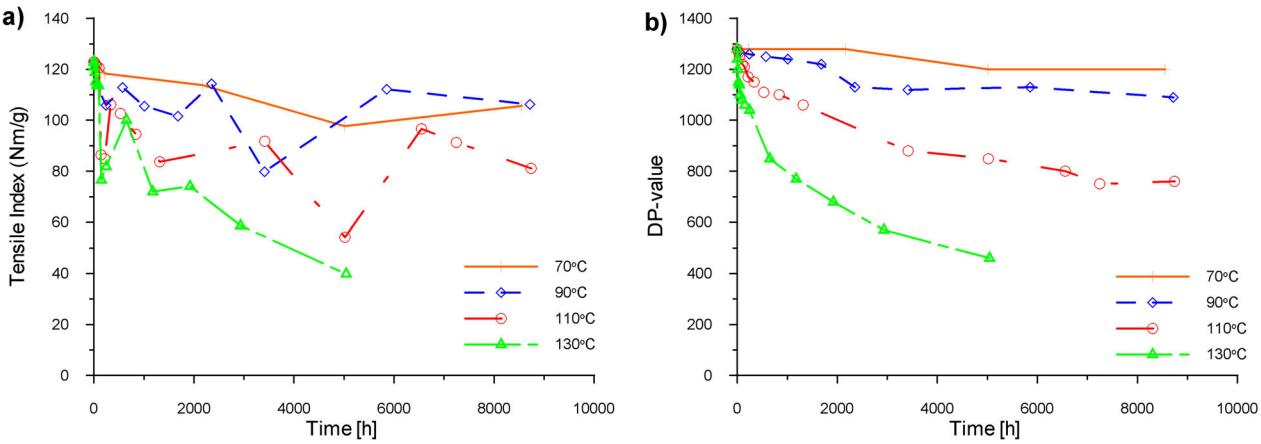


Figure 8: Tensile index (a) and DP-value (b) for Insuldur with 3% moisture added versus time.

As seen from Figure 7 and Figure 8 the DP-values develop uniformly, while the tensile index varies less systematically. For Insuldur the values appear quite confusing. We believe this to be due to the Insuldur paper being creped. For paper tested under other conditions the trends are similar. This is discussed in Section 3.3.

The correlation between the tensile index and the DP-value for the two paper types is plotted in Figure 9. For Kraft paper the correlation is quite systematic. The results for Insuldur are quite chaotic, and as mentioned above, probably due to the creping of the paper. Drawing an envelope curve for both plots indicate that the mechanical properties of Insuldur deteriorate quicker with falling DP-value than those of Kraft paper. Tests with non-creped thermally upgraded paper are needed to get a better knowledge of the correlation between mechanical properties and DP-value of thermally upgraded papers.

Attempts to correlate other mechanical parameters (i.e. percentage elongation at break, tensile energy absorption index and the modulus of elasticity index) to the DP-value did not reveal better correlations than what is seen in Figure 9.

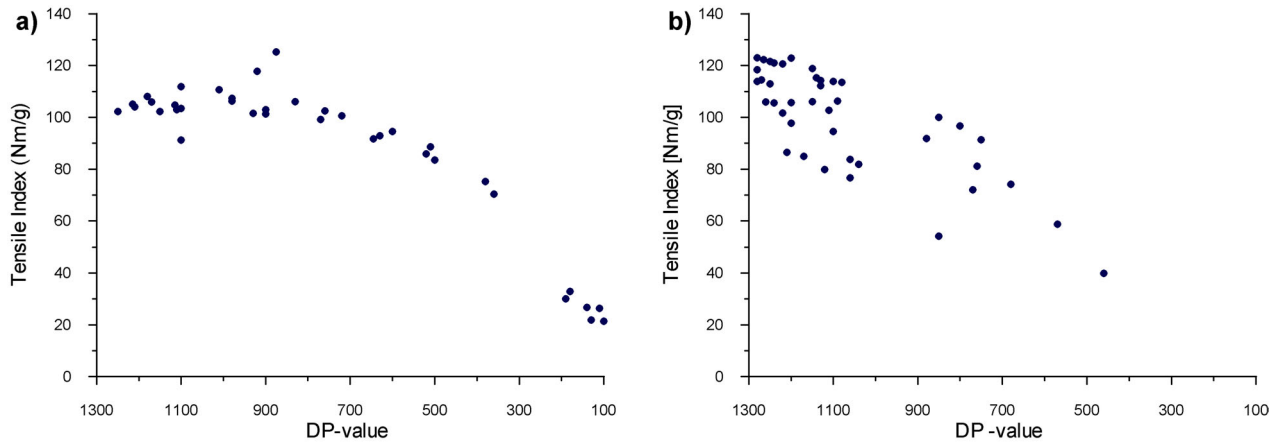


Figure 9: Correlation between tensile index and DP-value for (a) Kraft paper and (b) Insuldur.

3.3 Model parameters from ageing experiment

Generally, the experiments went well. One exception was the tests with molecular sieves put into the oil. This resulted in a very bad smell of the oil. Even though the oil was kept dry as planned and ageing rates stayed low we consider this experiment as being out of control.

The ageing model described in Section 2.2 has been used to analyse the data. For each test condition and temperature 1/DP was plotted versus time. The initial and the average rate of rise were calculated as seen in Figure 10. The average rate is calculated as a straight line using a linear regression of all data for a test series. The curve shape seen in Figure 10 can be compared with what is shown in Figure 4b for other temperatures. The fact that the reaction rate of average depolymerisation changes with time can for example be explained by different ageing rates for amorphous and crystalline parts of the cellulose fibres. We are not here investigating the applicability of more complex models that consider such effects. For those interested we refer to the PhD thesis of R. Heywood [10]. Table 5 to Table 8 show the calculated initial and average ageing rates (k) for Munksjø Kraft paper and Insuldur thermally upgraded paper respectively. The open cells (primarily at 70°C) are due to insufficient data and/or too small changes to make a calculation of any rate possible. For the lower temperatures (70 and 90°C) the ageing is very low and it is not possible to distinguish between initial and average depolymerisation.

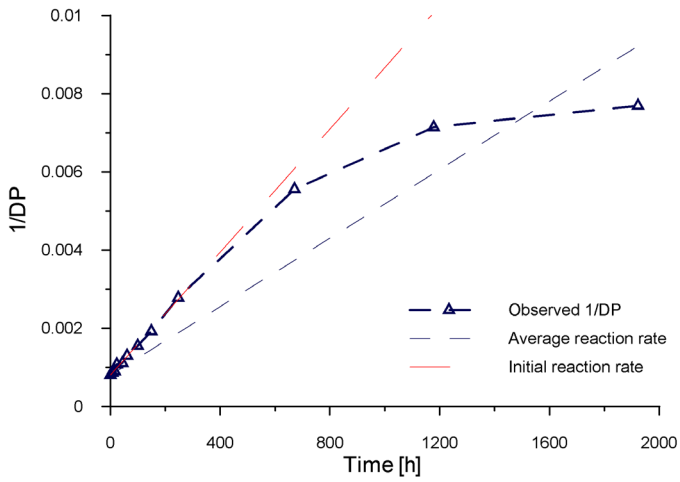


Figure 10: Example of calculation of average and initial reaction rates during an ageing experiment.

Table 5: Initial reaction rates for Kraft paper

Temperature	Reaction rates k [$DP^{-1}hour^{-1}$]					
	Dry paper	With Mol. sieve	Acidic oil	Oxygenated	1,5% water	3% water
70	1,18E-08	1,39E-08	1,66E-08	1,52E-08	4,41E-09	1,56E-08
90	1,78E-08	1,87E-08	3,05E-08	1,62E-07	9,61E-08	1,89E-07
110	2,07E-07	2,22E-07	3,95E-07	6,72E-07	5,46E-07	3,13E-06
130	1,57E-06	9,16E-07	1,90E-06	2,39E-06	3,35E-06	7,87E-06

Table 6: Average reaction rates for Kraft paper

Temperature	Reaction rates k [$DP^{-1}hour^{-1}$]					
	Dry paper	With Mol. sieve	Acidic oil	Oxygenated	1,5% water	3% water
70	1,18E-08	1,39E-08	1,66E-08	1,52E-08	4,41E-09	1,56E-08
90	1,78E-08	1,87E-08	3,04E-08	6,57E-08	4,17E-08	1,42E-07
110	9,56E-08	1,43E-07	9,36E-08	4,45E-07	3,88E-07	1,47E-06
130	2,78E-07	3,55E-07	5,73E-07	1,01E-06	1,75E-06	4,83E-06

Table 7: Initial reaction rates for Insuldur

Temperature	Reaction rates k [$DP^{-1}hour^{-1}$]					
	Dry paper	With Mol. sieve	Acidic oil	Oxygenated	1,5% water	3% water
70			8,00E-10	3,80E-09	3,00E-09	7,10E-09
90	1,80E-08	1,90E-08	2,00E-08	8,00E-08	1,20E-08	2,90E-08
110	3,20E-08	1,00E-07	5,50E-08	2,20E-07	7,30E-08	3,50E-07
130	3,85E-07	1,25E-06	6,40E-07	1,00E-06	6,90E-07	2,40E-06

Table 8: Average reaction rates for Insuldur

Temperature	Reaction rates k [$DP^{-1}hour^{-1}$]					
	Dry paper	With Mol. sieve	Acidic oil	Oxygenated	1,5% water	3% water
70			7,70E-10	3,85E-09	2,60E-09	7,06E-09
90	7,30E-09	6,90E-09	1,98E-08	5,90E-08	1,01E-08	1,94E-08
110	3,64E-08	3,59E-07	3,06E-08	1,40E-07	1,29E-08	7,29E-08
130	1,14E-07	8,32E-07	1,55E-07	1,98E-07	1,55E-07	3,07E-07

The reaction rates shown in the tables are the basis for setting up Arrhenius plots. As explained above for each test condition we plot the natural logarithm of the reaction rate versus the inverse temperature. Figure 11 and Figure 12 show the plots for Kraft paper and Insuldur respectively. The light drawn dark dotted straight lines represent a linear regression of all data at the three highest temperatures. We excluded the data taken at 70 ^{o}C, as the experimental basis here is weak because the ageing is comparatively little advanced at the time of writing. We have to wait some years to improve the basis here. The equations shown in the plot describe this straight line.

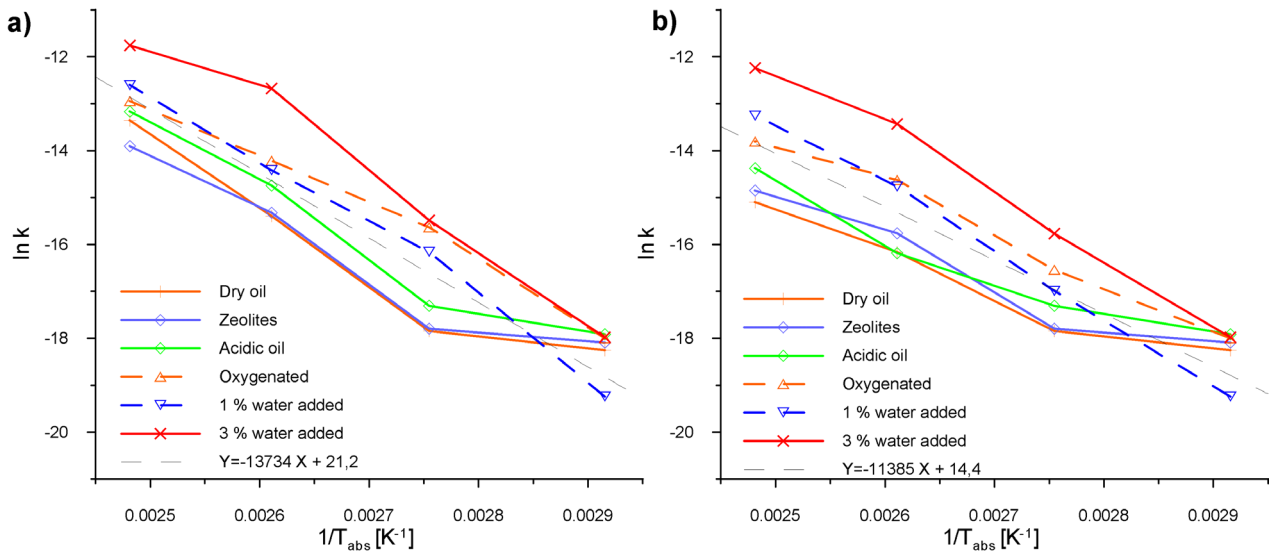


Figure 11: Arrhenius plots of (a) the initial and (b) the average reaction rates for Munksjø Kraft paper.

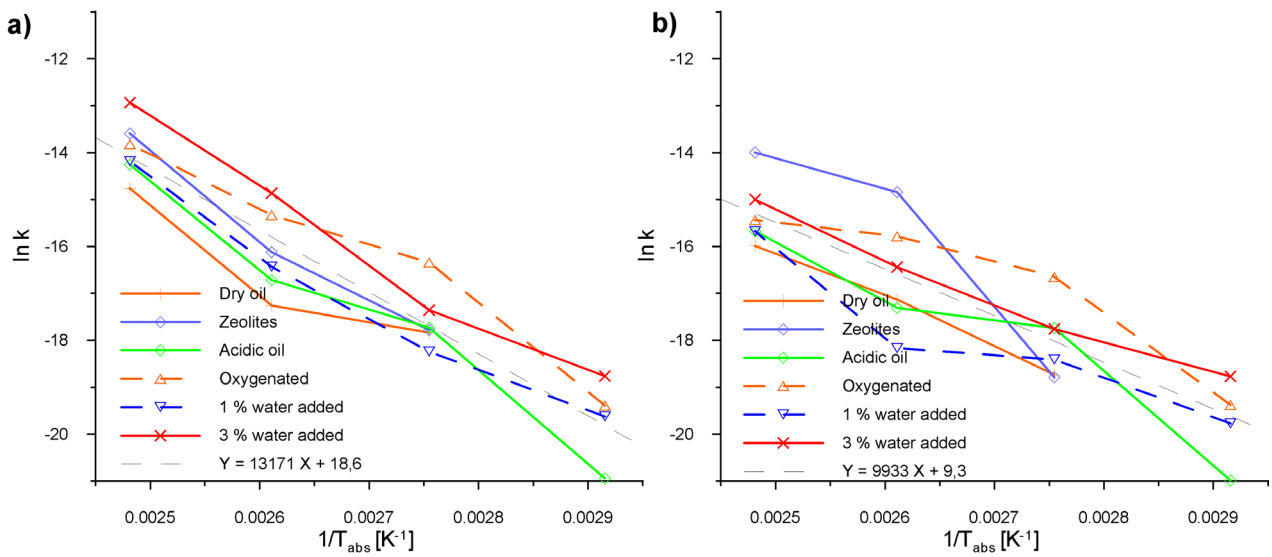


Figure 12: Arrhenius plots of (a) the initial and (b) the average reaction rates for Insuldur thermally upgraded paper.

Some features may immediately be observed: For Kraft paper the ageing is heavily accelerated when water is added (1% and 3%). Oxygen plays a minor role. Somewhat surprising is the fact that the acidic oil did not accelerate the ageing like expected. This may be due to low water content in these tests. Higher water content in the paper is expected to attract more acids into the paper. This leaves some questions, which need further investigations to be answered. For the Insuldur the aging rate is lower, and less influenced by increasing the humidity of the paper. Now the oxidation becomes more important. Figure 13 gives a better basis for comparing the ageing rates of the two paper types and the impact of water. For interpretation of the graph the reader is referred to Section 2.2.

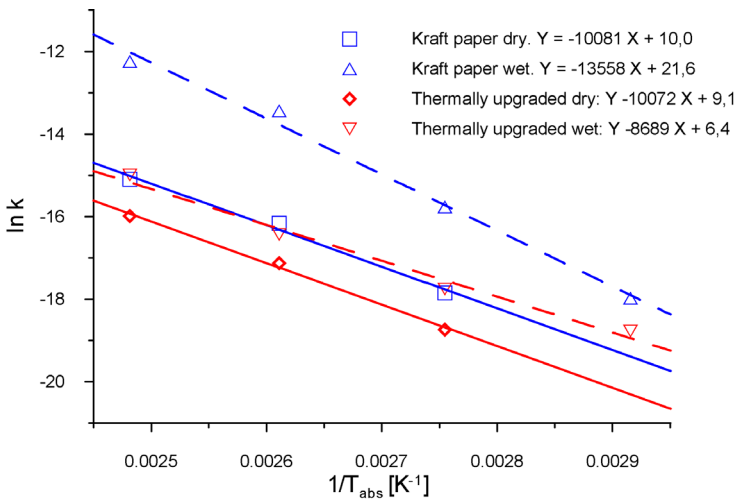


Figure 13: Comparison between Munksjø Kraft paper and Insuldur thermally upgraded paper .

The equations for the linear trend lines are given in the graphs. The coefficient (*B*) in front of x can be used to find the activation energy (*E*): $E = B \cdot R$, where R is the molar gas constant (8,314 $Jmol^{-1}K^{-1}$). Emsley studied the results from a large number of ageing experiments on Kraft paper and estimated E to be 111 ± 6 kJ/mole. The main body of the experiments he derived this figure from was done for temperatures above 110 °C, although for some stretched down to 90°C. From our experiments the linear regressions shown in Figure 11 and Figure 12 are used to find the activation energies shown in Table 9, assuming that the activation energy is the same for all temperatures and test conditions. Comparing the activation energy given from Emsley with our values based on the average rates – which seems most appropriate – shows that our activation energy for Kraft paper is lower. Insuldur shows an even lower value indicating that this paper type has an ageing rate that increases more slowly with increasing temperatures. It could happen that the activation energy varies somewhat with temperature, and that it becomes lower at lower temperatures (e.g. 130°C). Fallou [15] stated that the ageing rate was different below and above 130 °C. Emsley on the other hand treats the activation energy as constant over the full temperature range.

Table 9: Activation energies found in the present investigation.

	Initial ageing	Average ageing
Munksjø Kraft Paper	114 kJ/mole	95 kJ/mole
Insuldur thermally upgraded paper	110 kJ/mole	81 kJ/mole

To calculate the ageing and to make predictions for ageing we need both the activation energy (E) and the pre-exponential factor (A) from Equation (1). The value of A is strongly dependent on the test conditions. Furthermore, for each experiment several combinations of A and E can be used for fitting the theoretical ageing curve to the observed one. We make a fit of A after having found or chosen E. A varies wildly with the choice of activation energy E as can be seen from Table 10. (Note that A is the Y value found for the lines shown in Figure 13 when crossing the Y axis, which occur for 1/T equal to zero: A value far to the left of our figure found for infinitely high temperatures.) Table 10 shows the pre-exponential coefficients calculated from our test material using various activation energies. The corresponding coefficients (or interpolated values) from Emsley's work are also included. As can be seen from the table the pre-exponential coefficients

we find from our work end up quite close to the estimates of Emsley. It is up to the user to decide on which parameters to use in the life estimations. In the future, when the 90 and 70 ^{o}C experimental data has broadened, we will have a better fundament for estimating the activation energies in the lower temperature regime.

Table 10: Pre-exponential factors found for various activation energies.

Test Conditions	Emsley's Data		Present investigation		
	Kraft Paper E = 111 kJ/mole	95 % conf. bounds	Kraft Paper E = 111 kJ/mole	Kraft Paper E = 95 kJ/mole	Insuldur E = 81 kJ/mole
Dry and clean	$1{,}07 \times 10^8$	$0{,}2 - 4{,}7 \times 10^8$	$2{,}12 \pm 0{,}5 \times 10^8$ (+	$1{,}8 \pm 0{,}7 \times 10^6$ (+	$1{,}1 \pm 0{,}6 \times 10^4$ (+
With Mol. Sieve			$2{,}1 \pm 0{,}2 \times 10^8$ (+	$1{,}4 \pm 0{,}4 \times 10^6$ (+	$5{,}9 \pm 5{,}2 \times 10^4$ (+
Acidic oil			$2{,}4 \pm 0{,}7 \times 10^8$ (+	$1{,}7 \pm 0{,}6 \times 10^6$ (+	$1{,}2 \pm 0{,}7 \times 10^4$
Oxygenated	(21×10^8)		$8{,}3 \pm 2{,}8 \times 10^8$	$4{,}4 \pm 0{,}5 \times 10^6$	$4{,}0 \pm 1{,}8 \times 10^4$
1 % water added	$3{,}5 \times 10^8$	$0{,}8 – 15 \times 10^8$	$6{,}2 \pm 2{,}9 \times 10^8$	$4{,}2 \pm 3{,}2 \times 10^6$	$1{,}2 \pm 0{,}6 \times 10^4$
2%	$7{,}8 \times 10^8)$	$1{,}8 – 33 \times 10^8)$			
3,5- 4% water add	$3{,}5 \times 10^9$	$0{,}8 – 16 \times 10^9$	$21{,}0 \pm 7{,}8 \times 10^8$	$13{,}0 \pm 8{,}4 \times 10^6$	$2{,}7 \pm 1{,}2 \times 10^4$

+: Results from 70°C excluded

We can conclude that the experimental results as a whole are coherent with theories and data found in the literature and that parameters for estimating life consumption of a transformer can be derived from the test results. The results are in line with what is found in the literature. For Kraft paper water is the main ageing accelerating factor. A surprising result is the low impact on ageing from acidic components in the oil. It is possible that this is due to the paper being dry, and that we would have seen an accelerated ageing for paper with higher water content. Thermally upgraded paper was found to have lower activation energy than Kraft paper, and to be less sensitive to moisture.

3.4 Chemical by-products from paper ageing

During the experiments the water content, the acidity and the content of 2-furfuraldehyde (2FAL) were monitored. In the plots (i.e. Figures 14-19) the results from the series with molecular sieve and with the acidic oil were excluded. For the experiments performed on Kraft paper with oil taken from service an initial 2FAL content of 0,64 mg/kg was seen, For Kraft paper the concentration increased with time while for Insuldur the concentration fell with timeme. This indicates that this type of thermally upgraded paper consumes or binds 2FAL. The results from Kraft paper are in line with what can be seen in the literature, with a scatter of about 1 decade. For the thermally upgraded paper one can either conclude that this paper does not produce 2FAL, or that it consumes 2FAL. The fact that even for the used oil the 2FAL content fell to a low value supports the theory that it is consumed.

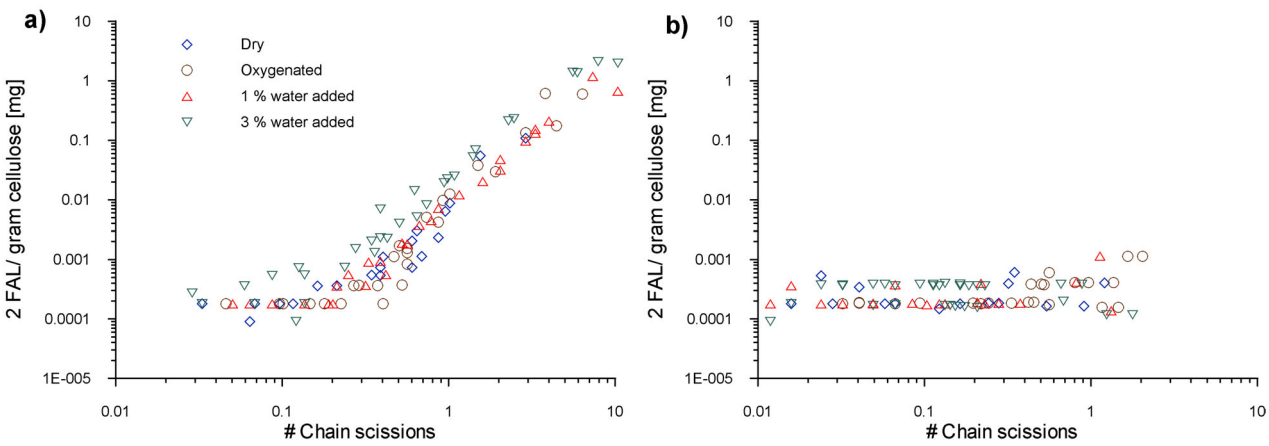


Figure 14: Content of 2FAL with ageing for a) Kraft paper and b) Insuldur.

The acidities of the paper and of the oil were measured throughout the experiments. As shown in Figure 15a the acidity increased much more quickly for the tests were water was added. In these tests depolymerisation was also faster. This all shows that in our tests the oil ageing produces insignificant amount of acids and that the paper ageing is an important source for acidic compounds. This can also be seen from Figure 15b. The role of the oil ageing may be different in a real transformer where catalytic processes on metal surfaces may add to the ageing of the oil.

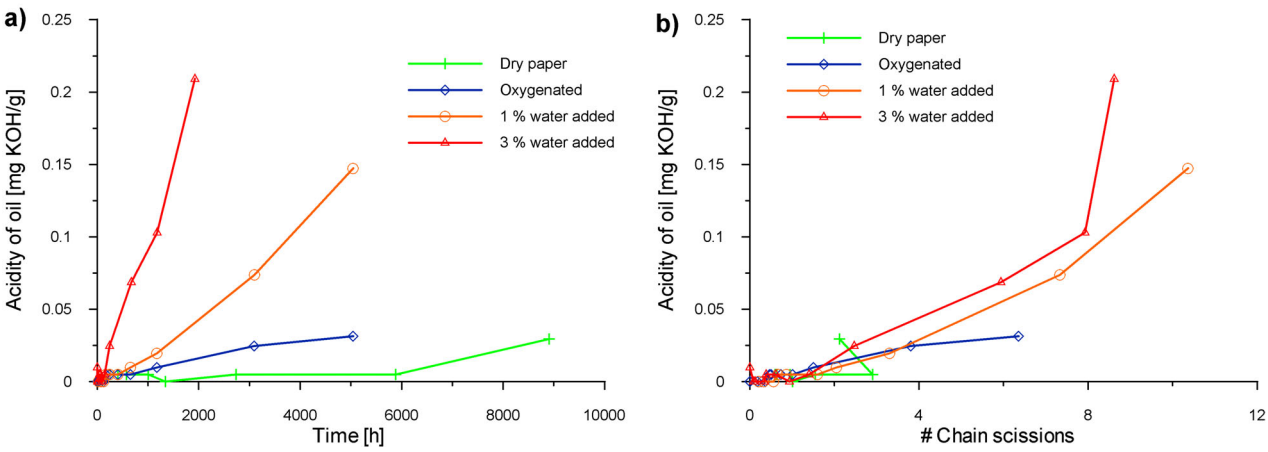


Figure 15: Acidity of oil (for experiments done on Kraft paper at 130°C: a) development with time and b) correlation with chain scissions.

Based on the measured acidity of oil and paper and the sample weights, the total amount of acidity was calculated and divided by the total weight of paper to get the production rate per gram paper. From these rates it appears that the thermally upgraded paper produces more acids than the Kraft paper as shown in Figure 16.

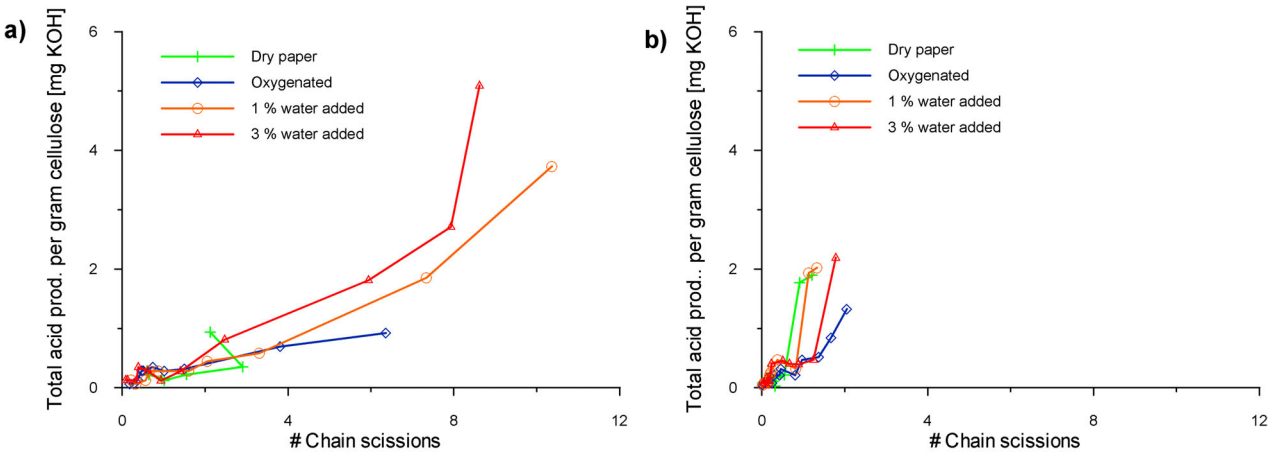


Figure 16: Total amount of acidity produced per gram of cellulose at 130°C for a) Kraft paper and b) Insuldur.

The content of water was measured both in the oil samples and in the paper. Based on this, the total water production was calculated considering also losses from the expansion volume above the oil during each sampling. The results from the moisture measurements on paper did not give reasonable results, probably because the paper samples lost moisture to the air when transferring them to the measuring apparatus. The most reliable moisture measurements were the measurements of the water in oil, where the sample was taken with a syringe and injected through a septum. Water in paper was therefore estimated from moisture balance with oil. Figure 17a shows how the water in the oil depends on the temperature and that the amount of water increases with paper ageing. In Figure 17b the water production per gram paper is shown. If these data are correct (they should be verified because they are based on several assumptions) the water production gives 4% water in the paper after 6 chain scissions (i.e. a DP value of 170). Among other things we have not compensated for an expected higher solubility for water in oil at the end of the experiments, when the acidity got higher (see 4.2.2).

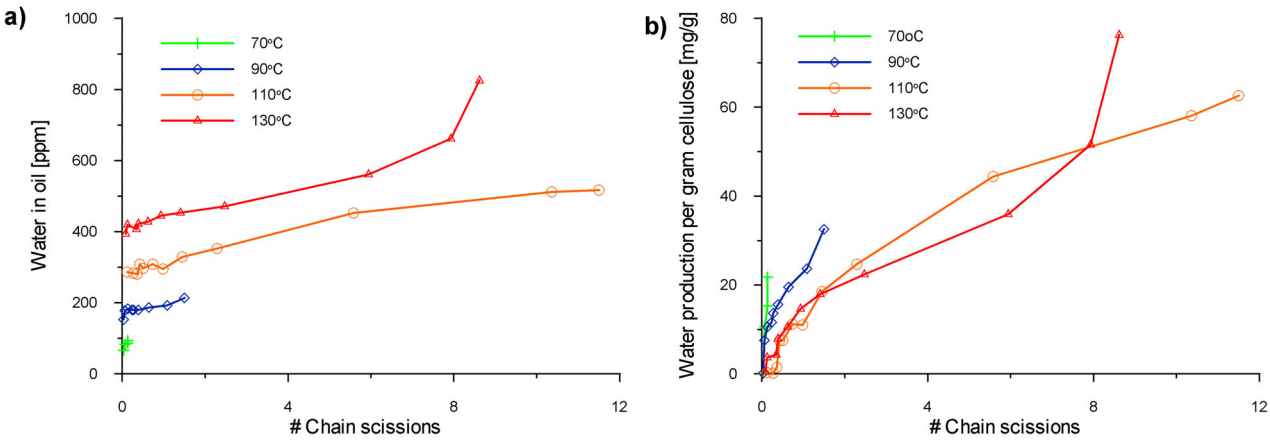


Figure 17: Water production from Kraft paper tests at 3% moisture added to paper: a) water concentration in oil versus chain scissions and b) total water production.

Figure 18, based on several experiments performed at 130°C, basically shows the same: The water concentration increases with increasing paper degradation and the depolymerisation of the paper becomes a significant source of water.

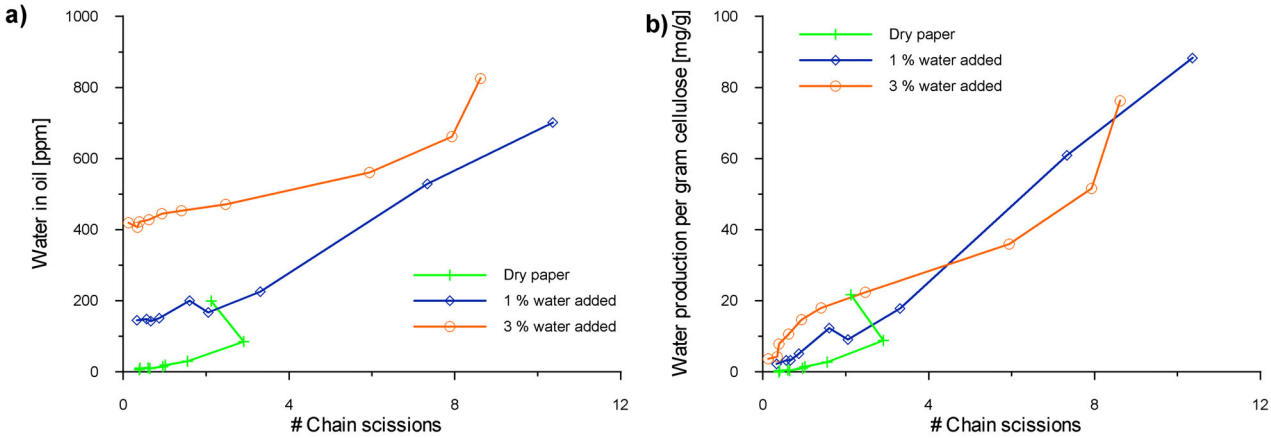


Figure 18: Water production from Kraft paper tests at 130°C: a) water concentration in oil versus chain scissions and b) total water production.

For the thermally upgraded paper the picture is quite contrary. When we added moisture the water content in the oil decayed or stayed constant like shown in Figure 19. Only for the dry paper could we see an increase in water content. Quite peculiar is the observation that we saw increased water content with ageing for dry paper and oxygenated oil at all temperatures. For moist paper we saw water consumption in most cases except for 1,5 % water at 130°C. However, we must here note that the total water production was found from moisture balance calculations, assuming that the ratio between water in oil and water in paper was constant and equal to what was initially measured when the experiment was started at a given temperature and moisture injection.

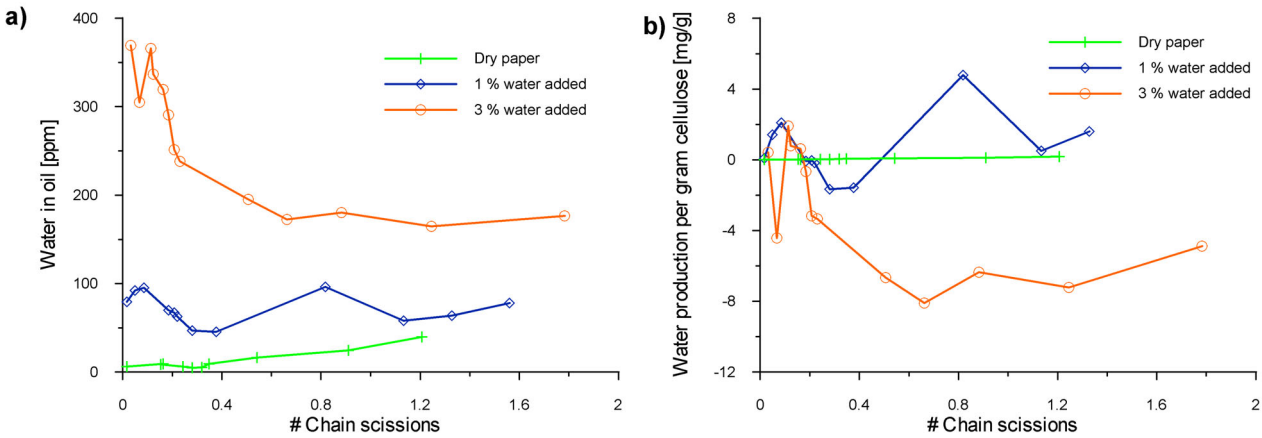


Figure 19: Water production from tests on thermally upgraded paper at 130°C: a) water concentration in oil versus chain scissions and b) total water production.

In our measurements, we have not measured the content of CO and CO_2. It is well known that these gases are produced during ageing of paper [16, 17]. Results found in the literature indicate that the production rate does not only depend on the paper degradation, but also temperature and moisture.

3.5 Speculations about acids and water.

In the literature it is claimed that the paper ageing is accelerated by acidic oil. However, acids do not seem to accelerate ageing for dry paper in our experiments. It may be that there is a synergy between acidity and water and that more water is needed in the paper to activate the impact from the acids. Generally, we lack knowledge on interaction/solubility balance for acids in oil and in paper. Experiments are needed to find the acid balance between paper and oil at various water contents and temperatures. This will help to understand the effects of oil reclaiming: How much acids do one manage to extract from the paper. Furthermore, ageing experiments with acidic oils taken from service combined with paper of various humidities are needed to learn whether this aspect is of importance or not. This will influence our attitude to oil reclaiming procedures.

The fact that the ageing rate for Kraft paper seems to decay with time (Figure 10) and the observation that the water content increases with time is intriguing. As water is generally found to be an ageing accelerator this indicate that the decay in the ageing rate with time with constant moisture content would have been even more pronounced. Could this be due to different activation energies for amorphous and crystalline cellulose?

The effect of water on Insuldur contrasts this. Here we see that water is consumed or bound and that the ageing rate and the influence of water are lower.

3.6 Experiences with Zeolites for drying oil

Molecular sieves has earlier been proposed and used as moisture traps to reduce the water content in the cellulose. The observation that they in our experiments obviously worked as a catalyst for oil ageing possibly puts an end to this idea. However, its presence had a positive effect on the paper ageing for the Kraft paper. For the thermally upgraded paper its presence had an accelerating effect on the ageing.

Possibly other types of molecular sieves may work better. The idea to remove the water from the paper just after it is formed has an obvious potential for life extension. The idea is by no means new [18]. The technique was developed to a commercial stage in England in 1973 under the name Transiv.

4 RESTORATION OF TRANSFORMERS

Guidelines for maintenance of oil and windings of power transformers.

Care should be taken to keep the content of inhibitors above 0,05 –0,1%. At the same time the oil should not be allowed to reach high acidities (e.g. > 0,1 mg KOH/g) to avoid increased contamination of the paper and formation of sludge. However, if the paper insulation has a high content of humidity oil reclamation is found to be of less value and one should first consider drying of the paper/pressboard in the windings to extend the life of the transformer winding. The best process for drying a transformer is the vapour-phase technique. For on-site use the hot-oil spray combined with LF-current heating of the winding is believed to be a good alternative. Smaller filters and on-line drying-degassing equipment developed for hydraulic systems are not considered efficient enough for use on wet transformers. Drying can reduce clamping forces of the winding and therefore retightening must be considered when drying a transformer winding.

4.1 The oil

After the oil has been aged or otherwise reduced in quality one may take several actions depending on the severity of the ageing [11 ,12 ,19]:

- *Reconditioning* means filtering and/or degassing, thereby reducing contents of water and solid contaminants and/or removing dissolved gasses in the oil. The reason for degassing lies mainly in a risk of bubble formation when the partial pressures of the dissolved gases (e.g. nitrogen) gets too high and therby a risk of low breakdown voltage of the oil.
- *Reinhibiting* is not much used in Norway, but may as discussed below be an inexpensive way of postponing more rigorous actions.
- *Reclamation* is a process (often combined with reconditioning and usually reinhibiting) where the ageing by-products are absorbed in chemical absorbents (e.g. Fuller's earth). The Fuller's earth can either be disposed or reactivated (e.g. Fluidex technique) after use. It is a large advantage if the temperature in the winding is kept above 78°C (the *aniline point* of the naphtenic oil) to allow sludge to be washed away and later absorbed in the Fuller's earth.
- Replacement is the most rigorous action. It is possibly not always more expensive than a reclamation, but definitely less environmentally friendly.

All the first three processes may be applied on energized units. This fact also increases the efficiency in many ways.

Lamarre [20] made experiments that show the possibilities and problems one is facing when considering how to treat aged oil. These experiments were performed on Voltesso 35, aged at 100°C in a flow of dry air and presence of copper. The results are shown in Figure 20. Here used oil means oil used until the inhibitor content was reduced to zero, while oxidized means a further oxidation till the acidity reached 0,2 mg KOH/g oil and interfacial tension had fallen below 10 mN/m. If only the inhibitor has been consumed it is possible to regain the characteristics of a new oil, while if the oxidation has gone too far the reclamation and reinhibiting of the oil does not help much. Finally, it looks as if a mere reinhibiting of the oil, which is an inexpensive process, may delay the need of a full reclamation.

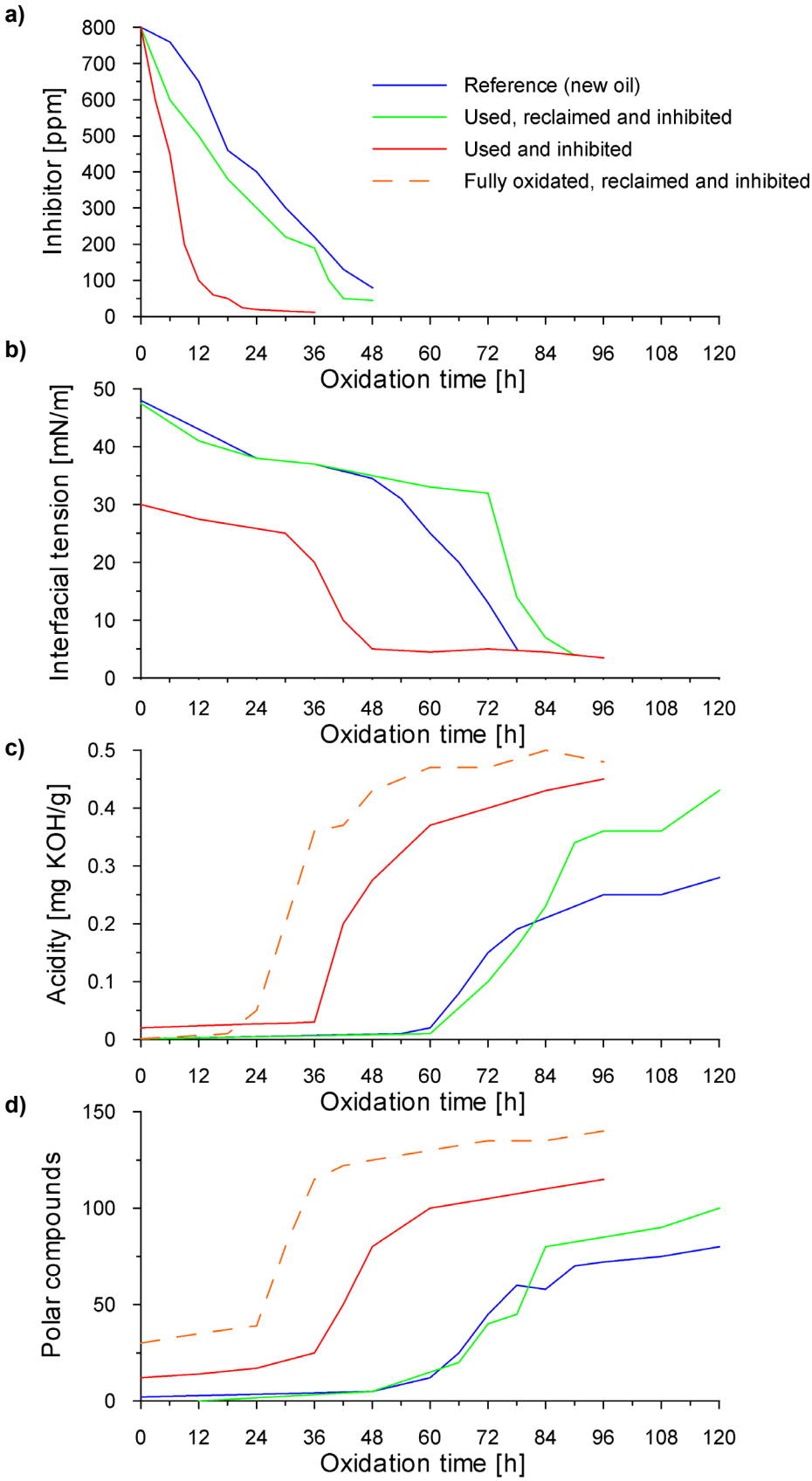


Figure 20: Inhibitor consumption (a), development of interfacial tension (b), acidity (c) and content of polar compounds (d) for new and aged oil after reclamation and/or reinhibiting of the oil. In Figure 20d polar compounds are given as the area under the peak in a HPLC (High Pressure Liquid Chromatography) diagram.

Depending on the severity of the oil ageing different options are available:

- If the oil is too aged (i.e. having an acidity above 0,5 mg KOH/g oil), then the oil is beyond hope and has to be renewed. It is in this case not possible to regain the good ageing characteristics of a new oil even after reclamation. This can also be seen from Figure 20 c and d. One must also consider that ageing by-products may remain in the paper and that they may introduce ageing of new oil after a refilling.
- IEEE [19] states that oils should be reclaimed when precipitable sludge is formed or the interfacial tension falls below 16mN/m. (Here IEC 60422 advocates "investigation" if the interfacial tension falls below 15 mN/m).

While oil reclamation was not considered previously in the Norwegian Oil Handbook, it now gives guiding values for when reclaiming should be considered (Figure 9).

Table 11: Norwegian guiding values for considering oil reclamation [12].

Parameter	Norwegian Oil Handbook
Inhibitor content	0,1 – 0,05 %
Neutralisation value	0,1 mg KOH/g
Interfacial tension	22 mN/m
Oxidation index *	300 - 30

*Oxidation index= interfacial tension/neutralization value

It is clear from Figure 20 that only adding new inhibitor at the moment the inhibitor is fully consumed does not improve the quality of the oil up to that of new oil. Companies in the reclaiming business (e.g. S.D.Myers) state that by merely replenishing inhibitors into the oil when they are fully consumed increases oil life to about 1/3 compared to doing this after a reclaiming of the oil. However, the costs of applying the two different processes will certainly be different and it may be economically profitable and technically viable to apply only a reinhibiting when the content of inhibitor has fallen to e.g. 20% of new value to postpone the cost of a full reclamation. There are commercial devices available for adding inhibitors like e.g. shown in Figure 21. As mentioned above, one should not expect the oil to last as long as a new oil, and acidity, interfacial tension and dielectric loss factor or conductivity should be monitored to take actions well before their values show signs of significant deterioration. There is no experience with such a maintenance scheme, but the potential cost-benefit indicates that the scheme should be tried and tested.

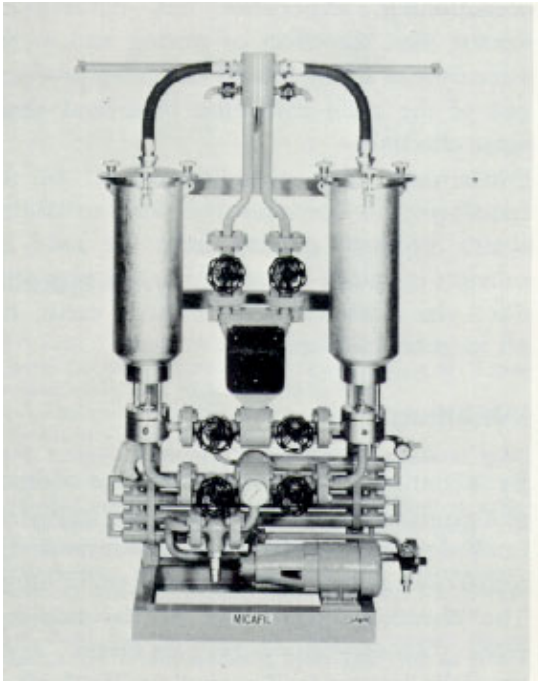


Figure 21: Inhibition device.

4.2 The winding

4.2.1 Life estimation of a transformer

The ageing kinetics is the basis of a model for ageing of a transformer winding insulation as described above. The model can be used as a tool for forecasting ageing development and for analysis of the impact from changes in operational conditions (i.e. load changes) like shown in Equation (3) and in Figure 22. The curves shown in the figure are calculated with a start and end-value of the DP of the paper of 1000 and 200 respectively.

$$Expected\ Life = \frac{\frac{1}{DP_{End}} - \frac{1}{1000}}{A * 24 * 365} * e^{\frac{13350}{T + 273}} \ [year] \qquad (3)$$

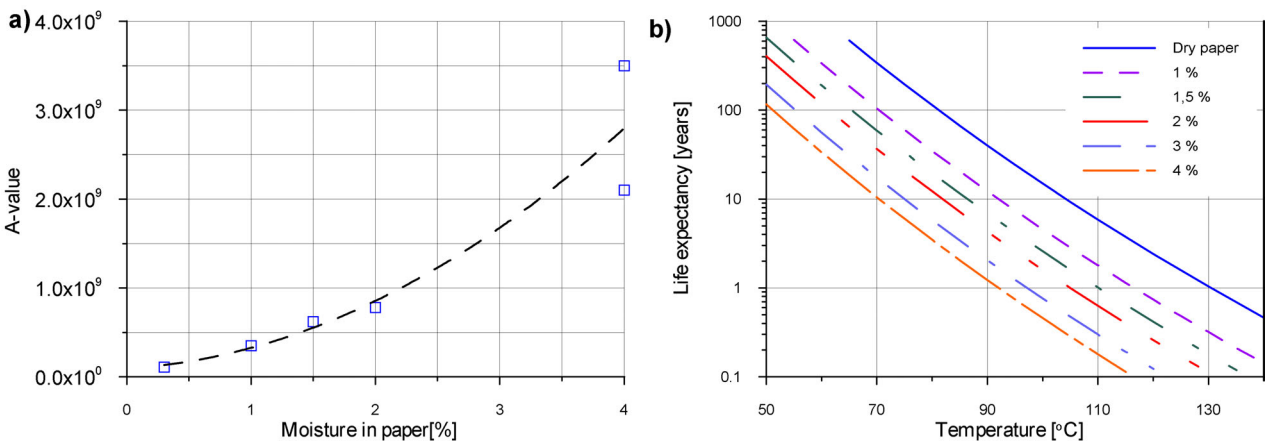


Figure 22: a) Pre-exponential values A found for various moisture contents in the present investigation and by Emsley [9]. b) Life expectancy for winding run at various temperatures and conditions.

Also the expected benefit (e.g. life extension) from maintenance actions (drying, oil reclamation) can be analysed like shown in Figure 23, where the cost of the drying process should be compared with the present value of a postponed investment. According to IEEE the following costs should be considered [19]:

1) Cost of materials
2) Disposition of service-aged or contaminated materials, or both
3) Total cost of process versus quality of end product
4) Equipment maintenance and amortization
5) Cost of collection and storage of oil
6) Labour and transportation costs
7) Laboratory costs
8) Cost and availability of new oil versus cost of reprocessed oil
9) Loss of oil during reprocessing
10) Cost and availability of oxidation inhibitors and cost of blending process
11) Value of service-aged oil when used for some other purpose

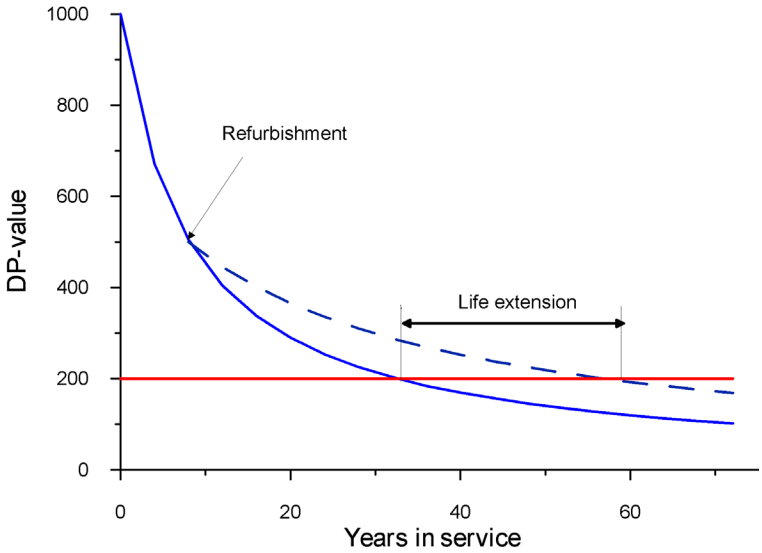


Figure 23: Principle behind cost benefit model for transformer maintenance.

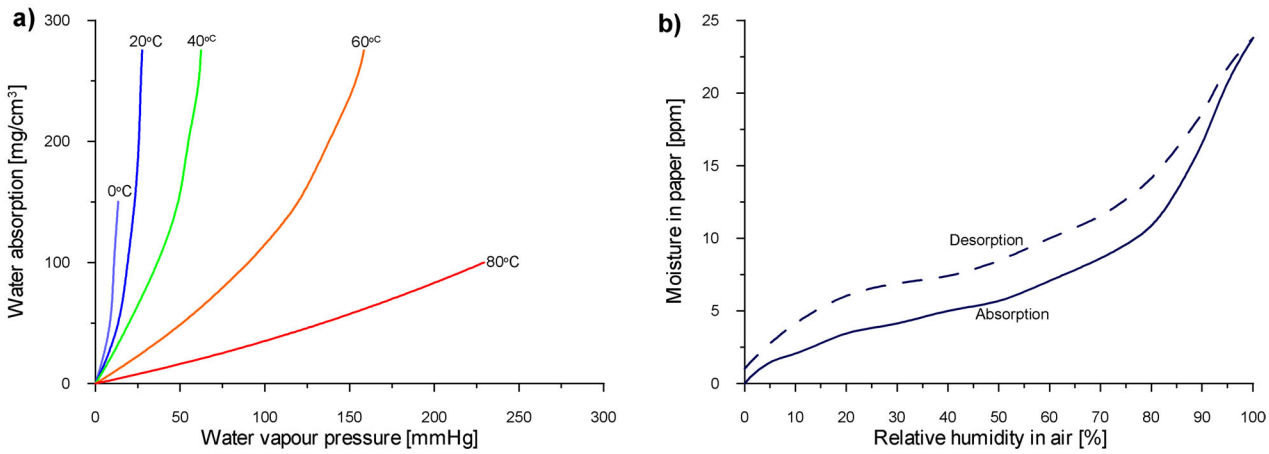
In principle the role of diagnostic actions is to reduce uncertainties in the estimation of the present technical condition of the transformer. The content of 2FAL, CO, CO_2, water and acids found in the oil can give indications of the condition of a specific unit, particularly if these parameters can be compared with those from other units. A nationwide database for results from Dissolved Gas Analysis (DGA) and oil data is now being established in Norway.

However, to get more accurate knowledge of the condition of a specific unit one needs samples of the paper taken from the winding or from a close-by location. To assess the validity of such samples one needs maps of how the DP-value will vary along and within a winding and down through the paper layers covering the conductors. Thus, a systematic mapping of scrapped units is important. Preferably this should be done on transformers where the thickness of the paper covering is representative of a high voltage transformer. To gain experience of the state of transformer windings (DP-values) from units where the load history and operational conditions are known is also an important element in building of a future knowledge base for transformer management.

4.2.2 Moisture concentration in paper/oil systems

Air-paper moisture balance is of importance during manufacturing, on-site erection and opening during service. A surface of 1000 m^2 will during 16 hours at 20°C absorb up to 8 kg of water for an air humidity of 40% [21]. For 70% air humidity the corresponding amount is 14 kg. For paper in air the moisture absorbed in the paper depends on the relative moisture in the air referred to the temperature of the paper. (The relative moisture is the water content compared to the saturation water concentration at the relevant paper temperature). Curves showing how the water content in paper varies with temperature and water vapour pressure can be seen in Figure 24a. It is the *relative humidity* of the atmosphere referred to the temperature of the paper that determines the moisture absorption in the paper like shown in Figure 24b.

The water content in the paper is strongly reduced with increasing temperatures in the paper for a certain vapour pressure in the atmosphere (Figure 24a). When the temperature is raised and the water concentration in the atmosphere is constant, then the relative humidity of the atmosphere just above the paper will be reduced and consequently the water concentration of the paper will also be reduced. Similarly, cooling the paper can increase its moisture content.



Temp[°C]	Pressure [mm Hg]	Density [g/m³]
0	6	4,9
10	10,2	9,4
20	17,5	17,3
30	32,6	30,4
40	55,1	51
60	149,2	130
80	355,1	293
100	760	598
140	2710	1968
180	7514	5150

Figure 24: Water content in paper at a) various water pressures [22] and b) relative humidity [23]. Table over water saturation pressures and water vapour densities versus temperature.

Oil-air moisture balance is important for how the oil absorbs water from the surrounding atmosphere like in e.g. expansion tanks. It is similar to the paper-air system: In an oil-air system the moisture absorbed in the oil will depend on the relative moisture of the air referred to the temperature of the oil. It is the condition just at the interface that counts. There has to be moisture balance (i.e. the same relative water concentration referred to saturation, disregarding differences between bonded and free water.) at the interface. The saturation water concentration in liquids

(e.g. hydrocarbons) varies with the type of liquid and the temperature as shown in Figure 25. Aged oil will have a higher saturation concentration than un-aged oil. This is due to a higher content of acids and polar compounds in the aged oil. Some indications of this is given in the standards [12].

Water solubility in oil is generally given in the Arrhenius form as shown in Equation 4:

$$r_S = A\, e^{\frac{-B}{T+273}} \tag{4}$$

Here r_S is the saturation solubility in oil in mg/kg (ppm), A and B are constants and T is the temperature in ^{o}Celcius. This formula is used to extrapolate the data for acidic oil in Figure 25.

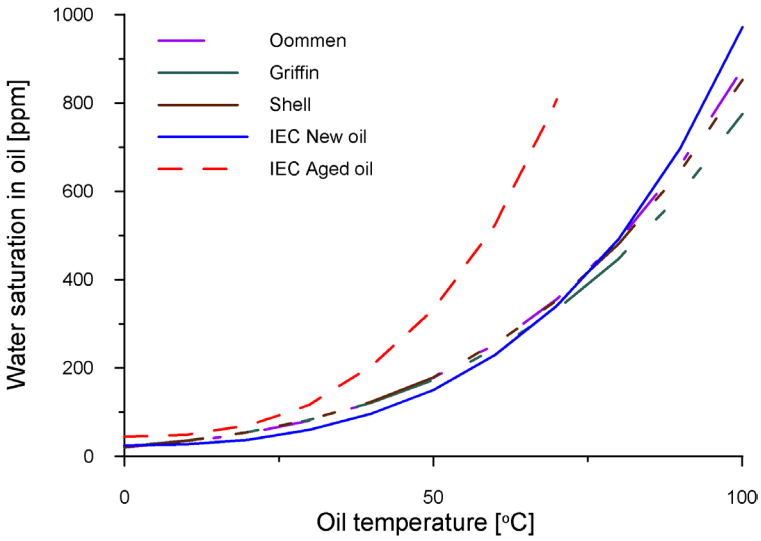


Figure 25: Saturation concentration of water in oils at different temperatures. Data from [24] and [12].

When measuring the moisture in a transformer we can disregard the water exchange with air and solely look at the moisture balance between oil and paper. The moisture in the paper is measured by taking an oil sample, and later estimating the moisture in the paper via moisture balance curves for oil-paper systems like e.g. those shown in Figure 26. To do be able to do this, one has to know the temperature of the paper (e.g. winding or barriers). Procedures for this estimation are described in the Norwegian Oil Handbook [12].

From the figures one can see that most of the water stays within the paper. From Figure 26 we can see that when measuring 30 mg/kg (ppm) water in the oil and having a temperature of 60°C the water content in the paper will be about 3%. In a 30 MVA transformer there will typically be about 20 tons of oil and 2 tons of cellulose. Thus there will be 0,6 kg water in the oil and 60 kg water in the paper. (It can be a problem for moisture estimation that there is a hysteresis in the absorption and desorption of water in the cellulose as shown in Figure 24b.)

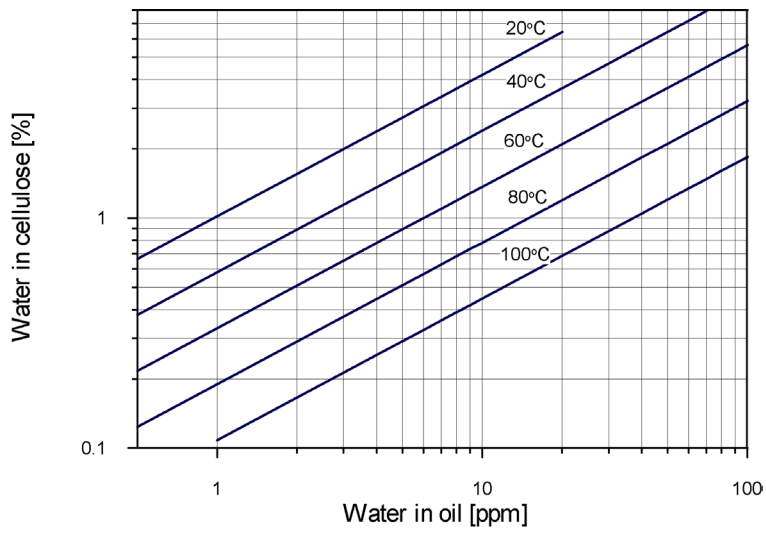


Figure 26: Moisture balance between oil and cellulose [25].

4.2.3 Drying of transformers: Moisture transport and the role of heating

When the transformer insulation is heated water moves from the paper to the surrounding air/oil. This is the basis for all procedures for drying of the paper insulation. Next one has to see to the moisture transport being as efficient as possible; both for the transport of moisture from the inner layers of the insulation to its surface, and for the transport of the moisture from the surface of the cellulose to the applied drying apparatus. Transport of moisture in a transformer is largely described by diffusion models. Diffusion is the process where water moves from locations with high moisture concentrations to locations with lower moisture concentrations.

Fick's laws describe the diffusion process. Fick's first law basically describes the mass transport (or flux) (F) as being proportional to the diffusion coefficient (D) and the gradient (i.e.difference) in moisture concentration C. | For one-dimensional transport (e.g. thin sheets) one gets:

$$F = -D \frac{\partial C}{\partial x} \tag{5}$$

If this equation is combined with the equation of continuity one gets Fick's second law, that essentially expresses how the concentration (C) varies with time:

$$\frac{d\,C}{d\,t} = D \frac{\partial^2 C}{\partial x^2} \tag{6}$$

In a transformer one can often simplify the geometry and use planar one-dimensional geometries as used above.

The diffusion coefficient will increase with temperature. No good data has been found for moisture diffusion in oil impregnated paper or pressboard. M.Zahn gives some data for oil and for un-impregnated pressboard shown in Figure 27 [26].

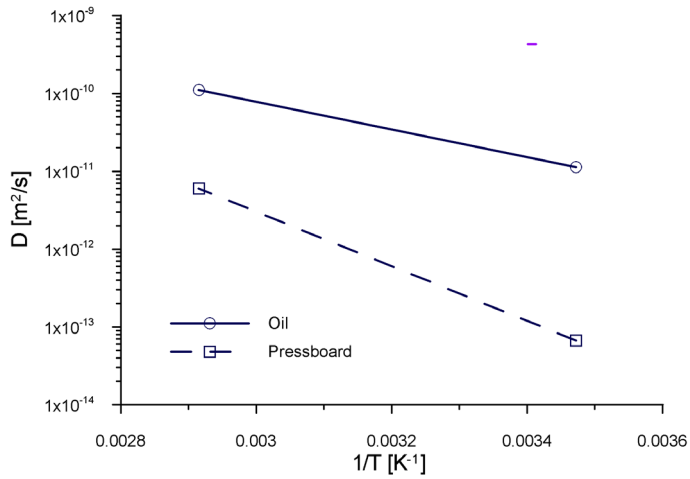


Figure 27: Arrhenius plot of diffusion coefficient of oil and un-impregnated pressboard.

However, to complicate matters the diffusion coefficient for pressboard (impregnated and un-impregnated) also increases with moisture concentration with a factor of 2 in the 0-5 % range [27, 28].

In an early paper, Lampe [27] calculates an expression for long times (> t_{max}) for planar structures of thickness *a* having an initial concentration C_0:

$$C(x,t > t_{\max}) = C_0 + \frac{4(C_b - C_0)}{\pi} * \sin(\pi \frac{x}{a}) * e^{-(\frac{\pi}{a})^2 Dt} \quad (7)$$

This expression is based on isothermal conditions. Setting x = a/2 will give the concentration in the middle of e.g. a pressboard barrier.

4.2.4 Methods for removing moisture from wet transformers

The time needed to dry a transformer depends on the amount of water absorbed in the insulation. To give an idea of the dimensions and weights of materials used in a transformer we have included some typical data in the table below.

Wood, pressboard and paper are hygroscopic materials. It is therefore necessary to dry a new or a wet transformer before filling it with oil. Moisture below 0,5% in the paper and pressboard should be expected for a new transformer.

Table 12: Typical design features of transformer insulation.

Item	300/60kV - 80 MVA	132/20 kV - 30 MVA
Thickness of paper on HV winding	2 mm two-sided	1 mm two-sided
Thickness of paper on LV winding	1 mm two-sided	0,6 mm two-sided
Coarse regulating winding	1,5-2,5 mm two-sided	
Fine regulating winding	2,9-4 mm two-sided	
Spacer thickness	3-4 mm	3-4 mm
Ribs	10 mm in stacks up to approx. 100 mm	10 mm in stacks up to approx. 100 mm
Barriers	3-5 mm inner winding support cylinder 1 mm in channels	3-5 mm inner winding support cylinder 1 mm in channels
Permawood details	50 mm range	
Weight of oil	27 tons	19 tons
Weight of cellulose	5 tons	2,2 tons

To describe the drying process of a transformer is complicated. By looking at an example and posing some simple questions, we will try to establish some simple guiding rules/parameters for evaluating the various reconditioning methods offered for on-site use. One has to ask:

1. How much water is present in the paper?
2. Which temperature is the winding heated to during drying and what is the concentration of water in the oil when in balance with the cellulose and when saturated at the given oil temperature?
3. How much water is the reconditioning equipment able to remove per day?

The first question is answered by measuring the content of water (see Section 4.3). When the design is known then the total amount of water is known.

The second is quite similar: When the temperature of the paper and its moisture are known one can calculate the moisture in the oil at a given temperature. Basically, the higher the temperature the more water one can get out of the paper and transported towards the drying equipment, both because the equilibrium is shifted towards more water in the oil or air/vacuum, and because the diffusion rate increases with increasing temperature.

Finally one has to look at the specifications of the drying and reconditioning equipment: What is the maximum throughput, down to what level will the oil be dried and are there any limitations in the water content at the input to get the promised result?

Let us have a look at to what extent transformer oil reconditioning or reclaiming can be expected to also result in drying of the cellulose. We have calculated some drying times as shown in Table 13. The table shows some important facts:

- Drying is more efficient for high water concentrations.
- To get the water out in an efficient way demands an increased temperature in the cellulose. (Here one should remember that not all cellulose is close to the heated winding.)

Table 13: Estimated efficiency of on-site drying of transformer done by oil circulating through a drying column. A 300 kV 80MVA transformer with 27 tons of oil and 5 tons of cellulose. Capacity of drying equipment: 5000 litres/hour with removal of all water during each pass.

Humidity in cellulose	Weight water in cellulose [kg]	Weight water in oil at 20°C [kg]	Weight water in oil at 70°C [kg]	Concentration at 20°C [µg/Litre]	Concentration at 70°C [µg/Litre]	Water removed per hour at 20°C [kg]	Water removed per hour at 70°C [kg]	Time to reduce humidity by 1% at 20°C [days]	Time to reduce humidity by 1% at 70°C [days]
1%	50	0,027	0,270	0,9	9	0.0045	0,045	463	46
2%	100	0,081	0,810	2,7	27	0,0135	0,135	154	15
3%	150	0,162	1,89	5,4	63	0,027	0,315	77	7

However, the table above is surely an oversimplification. Transformers and nature are more complex:

- The oil in the transformer will be a blend of unconditioned and reconditioned oil.
- The paper is not an ideal reservoir of water. When the surface is dried out water has to diffuse out from the deeper layers to the surface.
- The water has to be transported from the paper to the drying column carried by the oil. This presumably takes place by both convection and circulation of the oil.

The example given above is brought up because it has relevance for the methods offered for on-site oil reconditioning or reclamation hitherto. The drying of the cellulose is a possible bonus effect from processes mainly focussed on degassing, reconditioning and reclaimation the oil itself. For all these methods the cellulose and pressboard are dried via the oil transported through the processing apparatus, most frequently while the transformer is in operation. The ability of the methods to get water and ageing by-products out of the winding will depend on, and increase with, the temperature of the insulation system in the transformer during the processing. To remove water will - as stated before - require time: temperature dependence of solubility and diffusion for water is basically known. Experiences with oil reconditioning in Sweden show that a performed reclaiming process reduced the water content in the cellulose “somewhat” from the original 3% to a level that was still above 2% [29]. For the acidic ageing by-products the solubilities in oil and paper remains unknown. This makes it difficult to assess the long-term effect oil reclaiming will have on the acidity in the paper. One can also question to which degree these methods will remove sludge from the insulation system. Methods requiring a full draining of the oil will be more efficient. Removal of sludge from the winding is probably more efficient with the hot oil-spray method mentioned below. Otherwise one has to increase the temperature above the so-called aniline temperature (78°C) to get rid of sludge.

The tables below show specifications of degassing equipments offered for oil reconditioning and reclaimation in the Norwegian market today. Normally the equipment will be put together from oil pumps, degassing columns and single or double stage vacuum pumps. Cost will to a large degree depend on whether one accepts unmanned operation or not.

Table 14: Micafil drying and degassing units (max 500 mg/kg water content of the oil at input).

Type	Capacity [l/h]	Heating capacity [kW]	Vacuum pump Capacity [m^3/h]	Max. remaining moisture after one pass [ppm]	Maximum recommended oil weight in transformer [tons]
VH-005	500	7,5	1*8	10	1,5
VH-010	1000	15	1*16	10	3
VH-020	2000	30	1*30	10	7
VH-040	4000	60	1*60	10	18
VH-060	6000	90	1*120	10	35
VH-020 R	2000	30	410	3	7
VH-040 R	4000	60	800	3	18
VH-060 R	6000	90	900	3	35
VH-061	3000	75	2*60	6	22-25
VH-121	6000	150	2*120	6	65-70
VH-201	10000	250	2*250	6	100-120

Table 15: Characteristic data for the Fluidex equipment.

Type	Capacity [l/h]	Heating capacity [kW]	Vacuum Pump Capacity [m^3/h]	Max. remaining Moisture After one pass [ppm]
E 300 - *)	300	6	16	<5
E 600 -	600	9	25	<5
E 1000 -	1000	18	40	<5
E 1800 -	1800	27	60	<5
E 3000 -	3000	45	100	<5
E 4500 -	4500	75	160	<5
E 7000 -	7000	105	250	<5
E 10000 -	10000	160	400	<5
E 16000 -	16000	250	700	<5
E 20000 -	20000	300	1000	<5

*) OPTIONS:
B - vacuum booster
C - activated clay filter
M - mobile installation
P - portable installation

Additionally, a reclamation unit containing Fuller's earth can be added to the degassing/drying and filtration units. For the Micafil equipment the Fuller's earth is supplied in cartridges which are exchanged when saturated. To get the ageing by-products out of the winding, several fast draining/filling cycles of the oil in the transformer combined with oil reclamation is recommended [30]. Extra storing tanks for oil are then needed. The main difference in the Fluidex process is that the Fuller's earth filters are regenerated during night time in a heat and vacuum process. The process is run continuously (degassing, drying and filtration) while the Fuller's earth treatment is only active during day-time.

To get a proper drying, one can dry the transformer after taking the transformer out of service and removing the oil. Up to now this has only been done in factory, but now such methods are being

offered for on-site use. In general draining the oil away and applying vacuum makes moisture transport easier than in oil, particularly when the drying can be done at elevated temperatures. In this case it will be the diffusion of the water through the paper that limits the drying.

Three different methods for drying can be used. They are all based on drying of un-impregnated windings or windings where the oil has been drained away:

1. *Hot oil spray;* Hot oil is sprayed onto the windings to heat the cellulose and evaporate the water, which thereafter is removed by vacuum.
2. *Vapour phase;* A hydrocarbon liquid (kerosene) is evaporated whereafter it condenses on the insulation thereby heating it. Water then evaporates from the cellulose. Finally the water and kerosene vapours are extracted by vacuum pumps and later separated.
3. *Hot air – vacuum;* Here both hot air blowing to heat and evaporate water, and vacuum to remove it, are used.

The methods are listed according to their ranked efficiency – the hot oil spray being the most efficient [27]. However, the hot vapour used in the vapour phase techniques will condense on all cold surfaces, while the hot oil will hit the first surface and be less efficient for "screened" parts [31]. One has to apply vacuum for a sufficiently long period to extract the water from the wood, the paper and the pressboard. In some processes the winding is heated by applying low frequency current during the drying process. This will definitively improve drying of the winding. How much it will help on ribs and barriers has to be verified. When using these methods one has to have storage tanks for the oil. Insulating the transformer tank will improve the heating efficiency.

Several types of small-scale equipment intended for permanent installation and continuous operation on the transformer are now marketed. Much of this equipment originally is equipment for use on hydraulic oils. The oil volumes in a hydraulic system is much smaller than those found in a transformer. This type of equipment will hardly have any significant impact on a heavily aged transformer with wet cellulose.

4.2.5 Methods for keeping water away from dry transformers

Less efficient techniques, like those mentioned above, may be justified for use on newly installed, still clean and dry transformers to avoid future acceleration of the ageing of the paper by keeping the water content low. There is a risk that some of these apparatus (i.e. on-line degassing units) may mask defects and hamper possible observation of defects in DGA analysis.

Zeolites (or molecular sieves) is a group of porous materials. For lower temperatures they are chemically inert. They come with various specified pore sizes and are used as absorbers for e.g. liquids or gases. They are able to absorb some 20% (by weight) of water, and may be restored in e.g. a vacuum oven. The smaller pore sizes (e.g. 3-5 Ångstrom) will allow water to be absorbed, while most gases have too large molecules to be absorbed. A filter based on molecular sieves would absorb water and could be feasible for keeping moisture low in new transformers thereby avoiding depolymerisation and further increase of water content. The sieves of lower pore sizes would pose a risk for changing the hydrogen content in the oil, thereby masking some defects from being detectable through DGA. However, large molecules like e.g. CO_2 would not be

absorbed. Due to our experiences with the zeolites acting as catalysts for oil ageing we cannot yet advocate these techniques. Possibly other types of filters may exist, but care has to be taken to verify and check the effects of such molecular sieves [18].

It has been proposed [18] to introduce a freezing trap (using e.g. a Peltier element) in the breather where water drops would be formed. These would settle out from the gas stream down to a reservoir, which could be regularly emptied.

Similarly, it has been proposed to insert a cellulose filter in the oil circulation [32]. If this unit is cooled then the humidity balance will be different here from inside the transformer. The oil will carry less moisture. The paper in the filter will absorb the excess moisture from the oil. This way the oil in the transformer – and thereby also the cellulose in the windings - is continuously dried.

Finally there is the technique of introducing a rubber sack or barrier into the conservator to reduce gas and water absorption from air into the oil. This should in principle work, and the technique has been taken into use by Norwegian utilities. However, the technique does not remove water that has already been absorbed, and does not prevent water from being formed in the paper during ageing.

4.2.6 Acids in the insulation system

Acids are known to accelerate the ageing of paper. However, the behaviour of acids in paper-oil systems still remains unknown. Lots of different acids are created during oxidation and ageing of the oil. In general, as both water and acids are polar, one would expect them to behave somewhat similar (i.e. have a higher solubility in paper than in oil). If this is true it will be as difficult to get acids out of the paper as it will be to get the water out. More research has to be done to get a better understanding of the situation. One can foresee that the solubility will – among other things – depend on moisture content and temperature of paper and oil.

Also more knowledge about acceleration of paper ageing caused by acids is needed before one can say how serious the problem is. Possibly some more information can be found from research on preservation of books in libraries and prints in art galleries.

4.2.7 Clamping forces

Increase of moisture in a transformer winding will result in swelling of the cellulose, increased clamping pressure and plastic deformation of the cellulose. After drying the paper will shrink. Due to the plastic deformation that has occurred a significant net reduction in clamping pressure is to be expected with slackness in the winding as a possible consequence. Additionally, when the paper in the winding ages, its density will be reduced. This process also leads to a reduced clamping force with time.

Transformer design and locally expected stresses should be considered when assessing the consequences of a possible winding slackness. On-site drying of aged and very moist transformers

without retightening the clamping should be considered risky until further studies of winding behaviour confirm or disqualify the above sketched scenario.

Even if one managed to dry and clean the insulation system to retard the ageing rate one has no guarantee that the situation is improved. Like wood, cellulose is strongly hygroscopic and does swell with increased moisture content. Consequently, it will shrink when the moisture is removed. For a winding, where the clamping pressure is essential to avoid displacement during short circuit stresses this has to be considered.

On one hand one needs to know how much the clamping pressure will change when the winding is dried, on the other hand one should also assess the stresses a transformer may be subjected to at its operating condition. Short circuit currents may vary with the location in the grid. The inductance between the transformer and the most likely location of a short circuit may also vary - again influencing the short circuit currents. One example here is the lightning protection ground wire above the power lines, which reduces risk of direct short circuit in the vicinity of the substations and power stations. Operational experience shows that there is a significant number of cases of transformer energising with a “forgotten” earthing apparatus near the transformer. This is possibly the most likely scenario for an old transformer. Even worse is the case where a transformer in a power station is connected with voltage in phase opposition to the grid voltage.

When a transformer is produced, the tolerances of the winding height are kept small because height differences between windings on the same leg will give extra stresses during short circuit. The winding (typically a disc winding) is made of copper conductors covered with Kraft paper. Between the discs there are spacers to create insulation distances, oil channels and cooling. After production the winding is dried and then pressed to a certain length by using hydraulic jacks. When mounted onto the transformer core it is giving a certain clamping pressure by means of pressing bolts. The bolts are fixed to the core. As the thermal expansion of the winding (cellulose and copper in series) and the core (steel) is different, the temperature cycling of the transformer will result in load cycles on the winding. If now the winding swells, the force will increase.

Some literature has been found. ABB Secheron has shown how length and pressure are related during precompression, drying, impregnation and final compression of a model winding [33]. A 1600 mm high model was precompressed with 1300 kN pressure down to 1540 mm height. Thereafter drying by heat and vacuum treatment was performed while the pressure of 1300 kN was kept on. The winding now shrunk another 40 mm (2,6%).

Then the winding was impregnated and a load cycle from 1300 kN to 0 kN and back up to 1300 kN was applied while expansion and compression were measured (see Figure 28). The hysteresis was minimal. During this cycle the total expansion/compression of the height was 0,9 %. Linearizing the curve around 1300 kN gives a dependence between force and shrinkage of $-4\cdot10^{-3}$ mm/kN or $0{,}3\cdot10^{-3}$ %/kN. Comparing with the 2,6 % shrinkage experienced during drying one immediately understands that the possibility of winding slackness after a drying of the cellulose should be taken seriously.

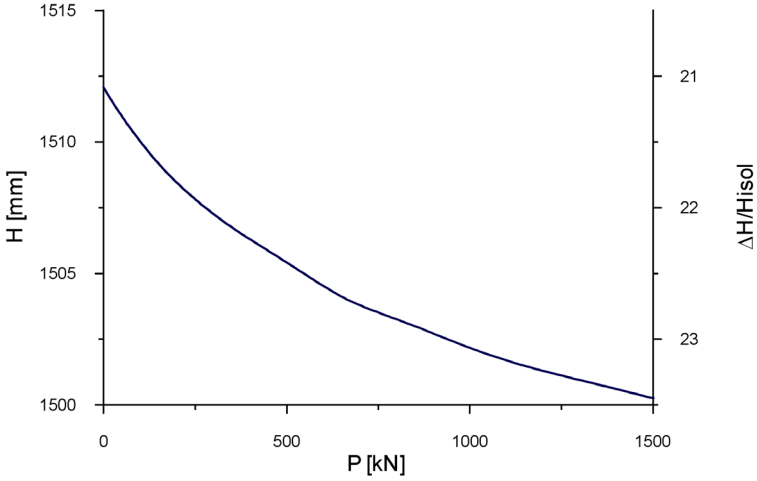


Figure 28: Winding height plotted against clamping pressure for model winding (Pressure: 3,2 N/mm^2).

An increase in the moisture will first lead to swelling of the paper and thereby to increased clamping pressure. As the paper is not a purely elastic material, some plastic deformation must be expected. It is the resulting deformation from increased pressure and numerous load cycles that establish the starting condition for results from a later drying process.

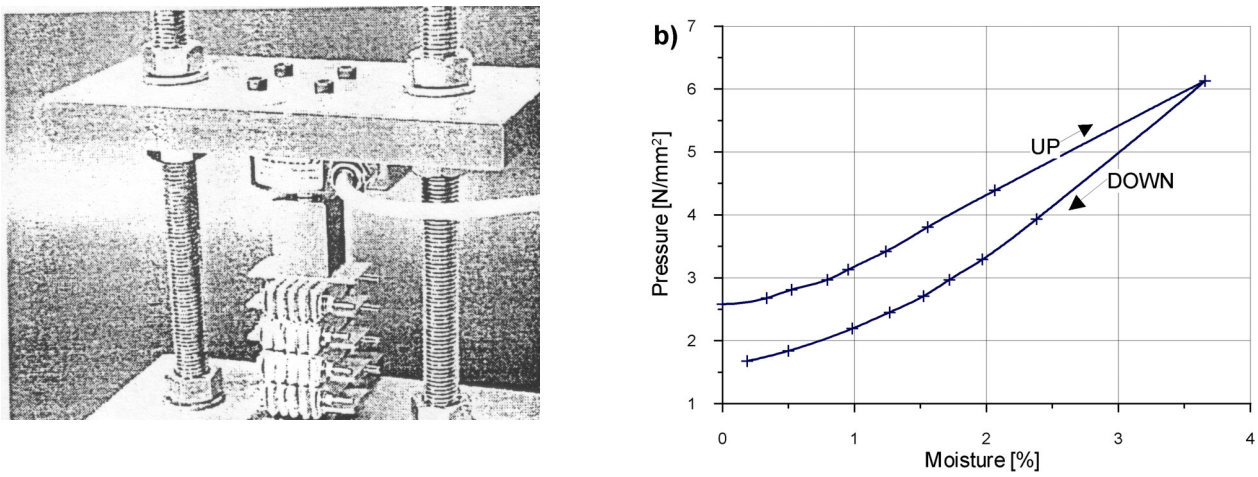


Figure 29: Experimental set-up for pressure: a) Model of winding and b) pressures relation with humidifying and drying the model.

At Weidmann some experiments on small models have been made [34]. A model of a disc winding with paper wrapped copper conductors and “radial “ spacers was made (see Figure 29). The pressure was applied over an area of 625 mm^2 (25 mm x 25 mm). Figure 29 shows how - for an unimpregnated model – the pressure increases with moisture. As the model thereafter is dried the pressure is again reduced. However, a reduction of 30 % in clamping pressure results. Similar results are also shown for impregnated models, now with a slower rate of increase of moisture due to the lower diffusion coefficient. It is commented that the process among other things depends on the ratio between metal and cellulose in the winding. Increased temperature in the transformer will enhance the pressure, as the thermal expansion of the paper/pressboard is higher than in the steel (leg of transformer).

This result was from one cycle with static pressure. During its life a real transformer will experience many load cycles while the paper swells. How this will influence the plastic deformation is not clear. Another factor that possibly should be considered is the long-term thermo-kinetic ageing of the paper, which may also result in shrinking and plastic deformation.

We have here mainly been concerned with the possible shrinking of the winding after a drying of the transformer, resulting in winding slackness. Manufacturers should also consider increase in pressure when the moisture increases.

4.3 How to measure water in the cellulose

Water in oil is normally measured using the Karl Fischer titration method. In modern instruments the titration is done automatically by coulometric methods. An oil sample with a known weight is injected into the test cell and the results are displayed on a screen in e.g. µg water in the oil sample. Both the sensitivity and the resolution will be in the 1 µg range. These instruments are laboratory instruments. Recently more field-suited instruments claimed to have a performance comparable to the Karl Fischer method have become available (e.g.. Aquadran 2000 from Syprotec). For online monitoring the Harley CT-800 moisture sensor or the Domino from Doble are possibilities. These instruments measure relative humidity. Possibly capacitive sensors like MMY 170 from General Eastern Instruments can also be used for monitoring.

In an oil-cellulose system the moisture concentration in the oil depends on the temperature. The paper can be considered “an infinite” reservoir of water in this context. When measuring the humidity in the transformer (i.e. in the cellulose) this is done by taking an oil sample and through the balance curves (Figure 26) find the moisture in the cellulose. To get a reliable result, the temperature in the transformer has to be known when the sample is taken. As described above it is the temperature of the cellulose that counts. Because the temperature varies along the winding one has to establish some kind of average temperature as the reference to use for later estimation of the water content in the cellulose. Temperature gradients in the transformer introduce uncertainties. It is also a great advantage if a stable load can be established for a period before the oil sample is taken. As mentioned above one has to compensate for changes in saturation if the oil is aged.

Modern delectric response methods offer possibilities for directly determining the content of water in the cellulose. These methods will give average moisture in the bulk of the solid. These methods are based on the fact that the polarisation time constants of oil and pressboard depend on the moisture content. Measurement of return voltage has been proposed, but simple measurements of polarisation and depolarisation currents offer simpler schemes for interpretation [35].

By connecting a voltage source between the LV and HV winding, applying a voltage step and measuring the polarisation current the time response of the insulation in the main gap can be recorded. If the design of the main gap is known (Figure 30a) one can make an equivalent circuit

of the gap (Figure 30b). From the measured time response (current decay) (Figure 30c) the moisture may be estimated. In the figure the step response is shown, and one can see that for longer relaxation times the current increases with moisture. A little simplified one can say that it is the conductivity of the oil that dominates in the start, while it is the conductivity of the pressboard that dominates for the longer times. Through a Fourier analysis one can link the results from a step response to those measured directly with a swept sine.

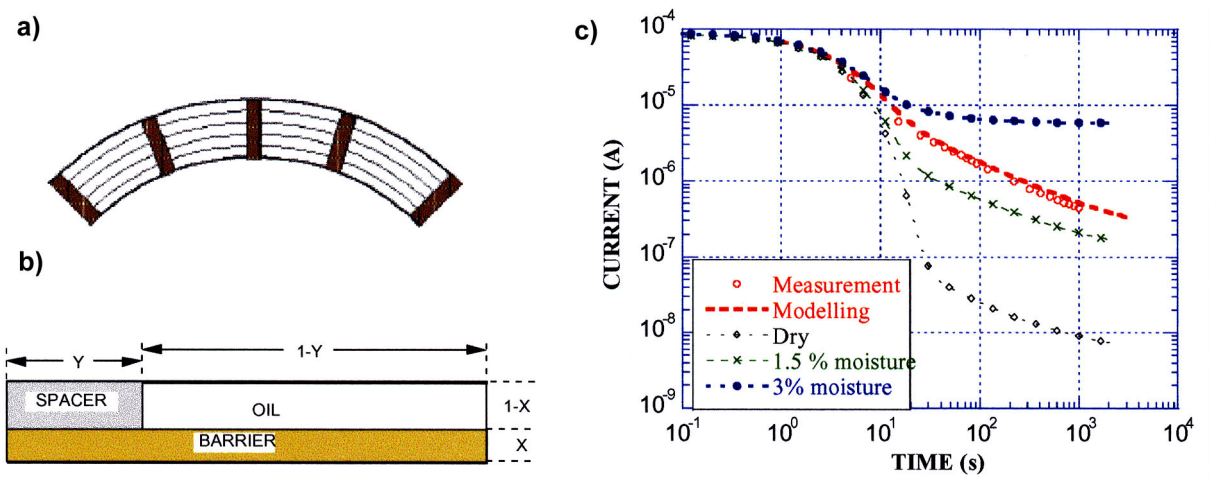


Figure 30: Measurement of dielectric response for estimation of water in cellulose [35].

5 EXPERIMENTS ON RESTORATION OF PAPER IN TRANSFORMERS

Description of model experiment on ageing Kraft paper with various refurbishment methods.

Moist paper (3%) was thermally aged at 110°C. After a certain ageing time the paper/oil system was refurbished. Only by active removal of the water could the ageing speed be reduced. Results indicate that there are some constituents in the paper, which bind water to the paper, and that these constituents are water-soluble.

5.1 Ageing experiment.

An experiment simulating various transformer refurbishment techniques was done. Paper samples were prepared and distributed in eight bottles as described in Section 3.1. Water was added to a humidity of 2,5 %. The bottles were placed in a heating cabinet set at 110°C. Ageing was started and continued until the paper was expected to have a DP around 600. Then six bottles that were to undergo a refurbishment were taken out, and experiments according to the following program were made:

- Two bottles are not treated.
- Oil is removed from two bottles prior to refilling with clean and dry oil.
- Oil is removed and paper dried (only vacuum for 3 days thereafter vacuum and heating to 80°C for 2 days) for two bottles prior to refilling with clean and dry oil.
- Oil is removed from two bottles and the paper put into distilled water for some days to remove acidic compounds. Thereafter the paper is gently dried under vacuum before the paper is reimpregnated with clean and dry oil.

Ageing and measurements are thereafter continued. This should in principle give indications of the benefit of maintenance actions.

5.2 Results from ageing experiment

When the paper was dried under heat and vacuum, the heating and degassing reduced the water content to about 1,3 % (half of what it was when it was taken out from the ageing experiment), while after the paper was put into water and then afterwards dried, the water content in the paper was reduced to less than 0,5 %. Similarly the water flushing reduced the acidity more than when it was only dried.

The results are shown in Figure 31. From this we can draw the following conclusions:

- Cleaning the oil only does not reduce ageing.
- Drying the paper reduces the ageing rate.
- Storing in water made it possible to dry the paper better. The ageing rate was further reduced in this experiment.

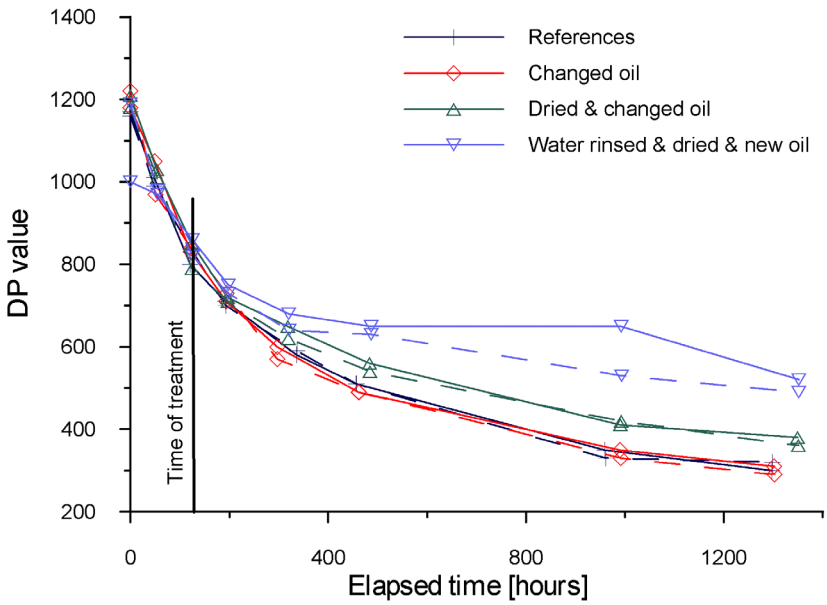


Figure 31: Impact from oil reclaiming and paper drying on ageing rate of paper in model experiment. Two tests, represented with one fully drawn and one dotted line, were made for each type of experiment.

We can conclude that the water has flushed away some constituents that bind water (and acids) to cellulose.

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